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Metabolic Costs and Biomechanics of Level Ambulation in a Planetary Suit

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Acronyms

ABF	Anthropometry and Biomechanics Facility
ACES	advanced crew escape suit
ACSM	American College of Sports Medicine
BW	body weight
CAD	computer-aided design
CG	center of gravity
CO_2	carbon dioxide
COTS	commercial off-the-shelf
CPHS	Committee for the Protection of Human Subjects
CTSD	Crew and Thermal Systems Division
CxP	Constellation Program
DNF	did not finish
ECG	electrocardiogram
EDS	energy dispersive spectroscopy
EPSP	EVA Physiology, Systems, and Performance Project
ESPO	EVA Systems Project Office
ESSPI	Earth shirtsleeve performance index
EVA	extravehicular activity
EWT	EVA Walkback Test
FY	fiscal year
GCPS	gravity compensation and performance scale
GRF	ground reaction force
HLT	hard lower torso
HUT	hard upper torso
IR	infrared
ISS	International Space Station
IST-1	Integrated Suit Test-1
JSC	NASA-Johnson Space Center
LCG	liquid cooling garment
MKIII	Mark III Advanced Space Suit Technology Demonstrator
N	Newtons
NBL	Neutral Buoyancy Laboratory
O_2	oxygen
PLSS	Portable Life Support System
PTS	preferred transition speed
ROM	range of motion
RPE	rating of perceived exertion
SE&I	systems engineering and integration
SVMF	Space Vehicle Mock-up Facility
TGAW	total gravity adjusted weight
V_E	rate of expiratory ventilation
VCO_2	rate of carbon dioxide output
VO_2	rate of oxygen consumption
VO_2pk	peak oxygen consumption

PREFACE

Although NASA's Apollo Program was a remarkable human achievement, fewer than 20 total program extravehicular activities (EVAs) were performed with no crew member performing more than three. With NASA planning to return to the moon to conduct thousands of EVAs, we believe that EVA systems need to be optimized for human performance and designs used during the Apollo Program had too many limitations to serve as the base designs for the Constellation Program. Our vision is to provide information so EVA systems can be developed resulting in low overhead and as close to or better performance than seen in the shirtsleeve environment on Earth. In this report, we not only highlight some of the factors that affect human performance during suited operations, but also describe testing methods, facilities, equipment, personnel, and future products so we can continue to build on the results of this test.

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1 INTRODUCTION

Our current understanding of suited human performance in reduced-gravity environments includes observations both from Apollo lunar surface extravehicular activities (EVAs) and from a limited group of studies conducted in partial-gravity simulation environments (1) (2). The Constellation Program (CxP) EVA Systems Project Office (ESPO), in concert with the EVA Physiology, Systems, and Performance Project (EPSP) and the Anthropometry and Biomechanics Facility (ABF), is developing design requirements for the next-generation lunar EVA suit and has initiated a series of tests to understand human performance and suit kinematics under a variety of simulated lunar EVA conditions. These studies, conducted in multiple partial-gravity environments, include matched unsuited controls so the specific metabolic costs and biomechanics of the suit can be understood. The eventual results of these studies will provide evidence-based recommendations for suit weight, mass, center of gravity (CG), pressure, and suit kinematic constraints that optimize human performance in partial-gravity environments.

The first of these studies, the EVA Walkback Test (EWT), was conducted using the Partial Gravity Simulator (nicknamed: POGO) in the Space Vehicle Mock-up Facility (SVMF) (NASA-Johnson Space Center (JSC), Bldg. 9) and the Mark III (MKIII) spacesuit. The MKIII was used as it represents a suit concept that provides the dynamic ranges of motion considered necessary for a wide variety of planetary tasks. Results from the EWT showed initial estimates for the total metabolic cost of suited locomotion in the reduced-gravity environments of the moon (1/6-g) and Mars (3/8-g) as well as preliminary biomechanical parameters (1). For this study, Integrated Suit Test-1 (IST-1), the suited conditions had a constant CG location and suit mass while the suit offload (weight), pressure, and suit kinematic constraints (waist rotation mobility locked vs. unlocked) were varied to determine their individual effects on lunar ambulation. For unsuited conditions, either the subject's mass was held constant while the offload was varied or the subject's weight was held constant while the subject's mass was varied.

This final report presents the key findings of IST-1 as it relates to suited and unsuited human performance of treadmill locomotion on the POGO. Additional tests have been completed or are being planned, to better understand human performance during exploration tasks and while wearing different suits as well as the limitations of testing in different lunar analog environments. The series of tests comprising IST-1 was conducted from March 6, 2007 through July 24, 2007.

1.1 Test Objectives – Primary

The purpose of IST-1 was to expand on the initial findings from the energy-velocity tests of the EWT. Specifically, the primary objectives of this test are to

1. Identify the individual contributions of weight, mass, pressure, and suit kinematics to the overall metabolic cost of the MKIII suit in its POGO configuration (121 kg [265 lb], including the mass of the Portable Life Support System (PLSS) mockup and gimbal, 29.6 kPa [4.3 psi]), during lunar ambulation.
2. Quantify the effects of the following factors on suited and/or unsuited metabolic rate, biomechanics, and subjective ratings during level ground ambulation at varied speeds:
   a. Suited – varied suit pressure at constant offload, mass, and CG

    b. Suited – varied suit offload (weight) at constant pressure, mass, and CG
    c. Unsuited – varied offload (weight) at constant mass and CG
    d. Unsuited – varied mass at constant offload and CG
3. Compare the MKIII at POGO configuration to the MKIII at POGO configuration with the waist bearing locked.
4. Develop predictive models of metabolic rate, subjective ratings, and suit kinematics based on measurable suit, task, and subject parameters.

1.2 Test Objectives – Additional

Beyond the primary objectives, additional scientific and engineering objectives and/or applications of IST-1 data were to

1. Define standard measures and protocols for objectively evaluating future exploration suit candidates and requirements verification of the flight suit.
2. Understand specific human performance limitations of the suit compared to matched shirt-sleeve controls.
3. Collect metabolic and ground-reaction force data to develop an EVA simulator for use on future pre-breathe protocol verification tests.
4. Provide data to estimate consumables usage for input to suit and PLSS design.
5. Assess the cardiovascular and resistance exercise associated with partial-gravity EVA for planning appropriate exploration exercise countermeasures.

2 METHODS

2.1 Subjects

Subjects were recruited from a pool of personnel who typically perform EVA-suited studies for the JSC Engineering Directorate and from the group of astronauts selected to support exploration EVA studies. Suit fit checks in the MKIII suit were performed on a range of subjects, and only those who had good suit fit were considered for inclusion in this study because of potential medical safety issues. From this list, six male astronaut subjects (Table 1) participated in the data collection phases of the study. One additional subject performed the VO_2pk (or peak oxygen consumption) test, but did not complete the data collection sessions because of poor suit fit. At the time of testing, no available female astronauts properly fit in the MKIII suit.

Table 1. Subject Characteristics

n = 6	Height (cm)	Body Mass (kg)	Age (years)	VO_2pk (ml/min/kg)	Leg Length (cm)
Average	179.1	80.7	44.8	50.8	104.0
Std. Dev.	4.8	8.5	6.9	6.7	3.8
Max.	185.9	86.4	52.0	60.7	109.2
Min.	174.6	68.2	37.0	42.6	100.2

All subjects successfully passed a modified U.S. Air Force Class III physical or equivalent examination. Each subject was provided verbal and written explanations of the testing protocols and the potential risks and hazards involved in the testing, and signed the JSC Human Research documentation indicating his understanding and consent. All testing protocols were reviewed and approved by JSC's Committee for the Protection of Human Subjects, and appropriate test readiness reviews were conducted before testing.

2.2 Test Hardware

2.2.1 Partial-gravity Simulator (POGO)

All IST-1 data collection sessions were performed using the SVMF's POGO system to provide simulated partial-gravity conditions. The POGO system and gimbal support structure were unchanged from those used during the EWT (1).

2.2.2 Mark III Advanced Spacesuit Technology Demonstrator Extravehicular Activity Suit

The MKIII suit (Figure 1) was used for suited testing, as it represents a suit concept that provides the dynamic ranges of motion considered necessary for a wide variety of planetary EVA tasks within today's technology level given other constraints that must be considered in pressure garment design. The suit also had an existing interface for integration with the POGO and allowed for varied-pressure testing. Thus, the MKIII provided a valid testbed from which attainable requirements for future suit development can be derived.

The MKIII is a hybrid spacesuit configuration composed of hard elements, such as a hard upper torso and brief section, and of soft components, such as fabric elbows and knees, designed to handle operating pressures of up to 55.0 kPa (8.0 psi). Another feature of the suit is the use of convolutes and bearings, allowing multi-axial mobility joint systems The shoulder is a rolling convolute with scye (armhole) and upper arm bearing. At the waist, both a bearing and a rolling convolute are used to allow flexion, extension, and rotation. Multiple bearings and convolutes at the hip and thigh allow abduction, adduction, flexion, and extension. The suit is entered through a hatch on the backside of the hard upper torso (rear entry suit) that also accommodates integration of a backpack PLSS. Subjects are stabilized in the suit by shoulder straps. The boots are modified commercial work boots with flexible soles for walking and a convoluted ankle joint for mobility. The MKIII has modular leg, arm, and boot soft-goods components that allow individualized adjustments with metal sizing rings. Foam padding is used to improve fit and avoid pressure or rubbing spots.

Different hard components materials can be used, depending on test objectives. The MKIII, as tested in IST-1, used the following components: volumetric backpack PLSS mockup (19 kg [42 lb]), aluminum hatch, aluminum hard upper torso (HUT), and composite brief and medium profile waist bearing. The gloves used during ambulation trials were series 4000 gloves because they were rated to higher pressures.

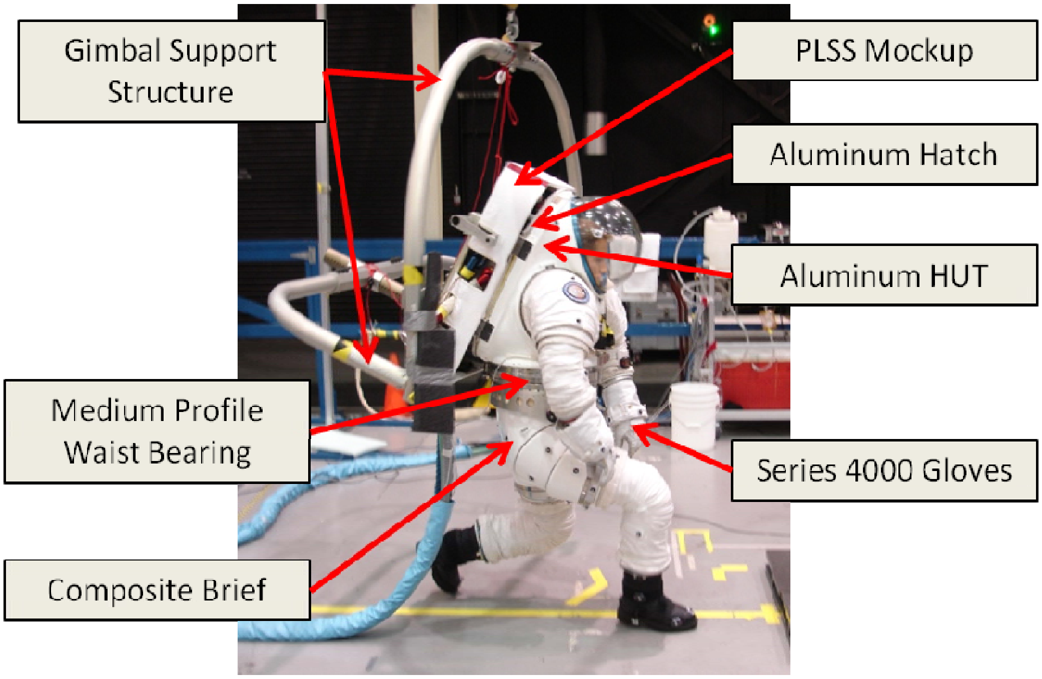

Figure 1. Mark III advanced spacesuit technology demonstrator.

During testing sessions, certified breathing air was provided by a compressed air tube trailer at a standard flow rate of 4.2 L/s (9.0 ft^3/min) through a manifold and transfer hoses and reduced to the appropriate pressure between 6.9 and 44.8 kPa (1.0 and 6.5 psi). Internal suit cooling was provided via a closed water loop that circulates through an ice/water chiller to cool the test subject's Class III modified shuttle liquid cooling garment (LCG). The system, which was powered by an external pump (~109 kg/hr), could deliver a minimum suit inlet temperature of 4ºC or a maximum of 28ºC when the chiller bypass valve was activated. Communication with the suited test subject was available via a system comprised of hardwire headsets.

For purposes of this report, "suit" refers to the pressure garment, PLSS mockup, and gimbal support structure.

2.2.3 Shirtsleeve Harness

Two separate harnesses were combined to allow for maximum range of motion and subject comfort. Figure 2 shows pictures of the harness components. The torso vest harness (Amspec no. JV0100P) (also known as a "jerk vest" in Hollywood) was combined with a Dakine Fusion kite surfing harness. The leg straps of the jerk vest were not used. Additional pickup points were sewed to the kite-surfing harness, allowing both harnesses to be connected via 2.5 cm (1-in). nylon webbing and buckles. Subjects were connected to the POGO spreader bar with four attachment points on the lower portion of the jerk vest.

Figure 2. Shirtsleeve harness components: AMSPEC, Inc. jerk vest and Dakine Fusion harness.

2.2.4 X-Vest

The X-Vest (Xtreme Worldwide Athletic Equipment, Houston) is a commercially available vest allowing the addition of up to 84 lb of mass in 1-lb increments (Figure 3). The vest, which is designed to serve as a training tool for athletes, members of the military, firefighters, and law enforcement personnel, allows the addition of significant mass while fitting tightly via elastic straps around the torso. The vest has eight rows on which weights can be added. In all cases, weights were added in equal proportion, front and back, with the weights going into the vest in the following order: 1. lower inside pockets, 2. upper inside pockets, 3. lower outside pockets, and 4. upper outside pockets. During trials, the vest was worn as the outermost garment on top of the subject's clothing and the shirtsleeve harness.

Figure 3. The X-Vest.

2.2.5 VacuMed Oversized Treadmill

The treadmill used for testing in the SVMF was a customized VacuMed model no. 13610 large research treadmill owned by the EVA & Spacesuit Systems Branch (Figure 4). With a walking surface 1.5 m wide and 2.4 m in length, it allows speeds from 0.2 to 12 m•s^{-1} (0.5 to 27.0 mph) with speed resolutions of 0.44 m•s^{-1} (0.1 mph) and grades from 10% decline to 30% incline. The treadmill was instrumented with four force plates (AMTI model no. OR6-5-2000) placed under the deck and belt of the treadmill. These were provided and integrated by the ABF. Placement of the four force plates allowed only normal forces to be calculated.

Figure 4. VacuMed research treadmill.

2.3 Testing Protocols

2.3.1 Peak Oxygen Consumption (VO_2pk) Test

To compare energy expenditure across the different conditions planned for this test, subjects performed a graded treadmill exercise test to determine their aerobic capacity via measurement of VO_2pk. The test began with a 5-min warm-up at 1.56 m•s^{-1} followed by three stages lasting 3 min each on a level surface, starting at 2.68 m•s^{-1} and increasing 0.45 m•s^{-1} at the start of each new stage. After the third stage, the speed remained the same and the incline on the treadmill surface was increased 3% at the start of each subsequent minute (3) (4). Subjects continued exercising through these stages as long as possible, to maximal effort. VO_2pk and peak heart rate were determined by the highest 1-min average attained during the test. From the VO_2pk, measured levels of energy expenditure during subsequent test sessions can be evaluated as percentages of VO_2pk to ensure subject safety and allow valid relative comparisons among subjects. This phase of IST-1 was performed from March 6, 2007 to May 18, 2007.

2.3.2 Establishment of Individualized Preferred Transition Speed

To establish accurate baseline metabolic and biomechanical data for a range of walking and running speeds, it was first necessary to determine the preferred transition speed (PTS) from walking to running. Therefore, before the unsuited energy velocity test, each subject's unsuited PTS was determined at 1/6-g using identical methods to those described in the EVA Walkback Report (1). Once the PTS was determined for each gravity level, three walking and three running velocities were assigned (Table 2) such that the PTS and the immediate range above and below it would be avoided during data collection. Three speeds were selected for data collection to allow investigators to understand the shape of the metabolic curve in both the walking and running ranges.

Table 2. Speeds Used for Data Collection

Stage	Speed	Comments
1	PTS minus 0.67 $m \bullet s^{-1}$ (1.5 mph)	Subtract 0.22 $m \bullet s^{-1}$ per stage; need smaller increments for walking
2	PTS minus 0.45 $m \bullet s^{-1}$ (1.0 mph)	
3	PTS minus 0.22 $m \bullet s^{-1}$ (0.5 mph)	Subtract 0.22 $m \bullet s^{-1}$ to assure walking out of transition zone
Preferred Transition Speed		**No data collected in transition zone**
4	PTS plus 0.22 $m \bullet s^{-1}$ (0.5 mph)	Add 0.22 $m \bullet s^{-1}$ to assure running out of transition zone
5	PTS plus 0.67 $m \bullet s^{-1}$ (1.5 mph)	Add 0.45 $m \bullet s^{-1}$ to distinguish metabolic and biomechanical differences at running speeds
6	PTS plus 1.12 $m \bullet s^{-1}$ (2.5 mph)	

2.3.3 POGO Offloading

Before the beginning of any trial, the target weight for the subject was verified with the integrated force plates in the treadmill. For suited tests, the target weight was adjusted to ± 0.5 kg (1 lb). During unsuited testing, the target weight was adjusted to ± 1.4 kg (3 lb) as this allowed for much quicker adjustments and minimized the overall time that a subject was suspended in the harness by the POGO.

2.3.4 Varied Mass Test (Unsuited)

Each subject translated on a level treadmill (0% grade) for 3 min at each of the six individually prescribed velocities based on PTS, while the POGO system provided partial weight relief. Subjects were offloaded to the weight that matched their weight during the suited trial with a suit system mass of 121 kg at lunar gravity (Figure 5). Subjects completed the six speed trial four times with each trial set at a different mass but a constant weight. Speed order was always from slowest to fastest for every condition tested. Masses of 0, 11.4, 22.7, and 34 kg (0, 25, 50, and 75 lb) were evenly distributed with respect to each subject's CG using the X-Vest, while each subject's overall weight was kept constant by increasing the POGO offloading force to offset the added mass in each condition. Varied mass trial order was balanced. Varied mass test conditions were performed between May 8 and July 24, 2007.

Figure 5. Instrumented unsuited subject performs treadmill locomotion while partially offloaded from POGO overhead.

2.3.5 Varied Pressure Test (Suited)

Each subject donned the MKIII suit with initial pressure of 29.6 kPa (4.3 psi) and in-suit oxygen concentration of 21% provided via certified breathing air as is customary during EVA test operations with the MKIII suit. Each subject translated on a level treadmill (0% grade) for 3 min at each of the six prescribed velocities while the POGO system provided partial weight relief to simulate lunar gravity (Figure 6). Subjects completed the ambulation trials at each of five different suit pressures: 6.9, 20.7, 29.6, 34.5, and 44.8 kPa (1.0, 3.0, 4.3, 5.0, and 6.5 psi). Varied pressure trial order was balanced. Suit mass was constant at 121 kg in these trials. Varied pressure test conditions were performed between March 22 and May 25, 2007.

Figure 6. Suited subject performs treadmill locomotion while partially suspended from POGO overhead.

2.3.6 Varied Weight Test (Unsuited and Suited)

Ambulation at the same six speeds used in the varied pressure and varied mass conditions was repeated in both suited and unsuited conditions at a range of simulated suit weights while holding mass (121 kg) and suit pressure (29.6 kPa [4.3 psi]) constant. For suited testing, POGO offloading force was adjusted to different gravity levels of 0.12-g, 0.17-g, 0.22-g, 0.27-g, and 0.32-g. For these trials, the mean total gravity adjusted weight (TGAW), which is defined as the suit, gimbal and subject mass (assume 80-kg subject) multiplied by the gravity level was 236, 334, 431, 529 and 627 Newtons (N) (53, 75, 97, 119, and 141 lb). If these were the actual TGAW on the Moon, it would require a suit mass of approximately 63, 121, 186, 247, and 308 kg. Unsuited testing was performed at the weight matched conditions of 0.17-g, 0.27-g, and 0.32-g. Varied weight test conditions were performed from April 4 to July 24, 2007.

By using a constant mass suit, no change was affected to the inertial properties or the mass distribution. Because suits of varied mass were not available and current POGO hardware does not provide the capability to lift significant added mass, the closest comparison we could make to understanding how a change in suit mass affects human performance was to simulate a change in mass by varying the offload level to see how a constant mass suit affected human performance at different TGAWs, otherwise known as weight on the ground. A combination of unsuited varied mass testing in this study as well as future suited and/or unsuited testing will be required to understand how the mass properties of the suit affect performance.

2.4 Metabolic Data Collection and Analysis

During VO_2pk and unsuited tests, metabolic rate was determined from continuous measurement of the rate oxygen consumption (VO_2), rate of carbon dioxide (CO) production (VCO_2), and rate of expiratory volume (V_E) using a headset/mouthpiece connected to a TrueOne® 2400 metabolic cart (Parvo Medics, Sandy, Utah). Heart rate during the VO_2pk test was monitored from 12-lead electrocardiogram (ECG) recordings and during submaximal tests from a heart rate monitor (Polar S-810i, Lake Success, NY).

During exercise in the MKIII suit, metabolic rate was based on measured suit ventilation rate, expired CO_2 concentration in the exhaust umbilical (CD-3A infrared CO_2 analyzer, AEI Technologies, Pittsburgh, Pa.) and the regression between VCO_2 and VO_2 as measured during the VO_2 peak test. This technique and this hardware were identical to those currently used during suited Neutral Buoyancy Laboratory (NBL) tests.

The metabolic rates represent the highest 1-min average during each of the 3-min walking or running stages. Metabolic rate was defined as mL of oxygen (O_2) consumed per kg of the subject's body mass per minute ($mL{\bullet}kg^{-1}{\bullet}min^{-1}$). Transport cost was defined as mL of O_2 consumed per kg of the subject's body mass per km traveled ($mL{\bullet}kg^{-1}{\bullet}km^{-1}$). Second-order polynomial regression trend lines were used to fit metabolic rate vs. the dependant variables.

2.4.1 Calculating Contributions of Weight, Inertial Mass, Pressure, and Suit Kinematics to the Overall Metabolic Cost of the MKIII Suit

Individual contributions to the total metabolic cost of the MKIII suit were based on a second-order polynomial regression model combining data from IST-1 and the unsuited baseline data from the EWT (1). The unsuited baseline and suited metabolic rates were calculated by using the regression equation relating speed to metabolic rate. The total metabolic cost of the suit was determined by subtracting unsuited trials from suited trials. Two different models exist because of different methods of calculating the cost of weight. In the unsuited-weight cost model, the metabolic cost of weight was determined by calculating the difference between unsuited and unsuited weight-matched trials. In the suited-weight cost model, the cost of weight was determined by extrapolating regression equations back to a 0.0-N suit weight and calculating the difference between 0.0 and 1,187 N (121 kg). Models discussed in this report used the unsuited-weight cost model. The cost of suit pressure was determined by extrapolating regression equations back to 0.0 kPa and determining the difference between 0.0 and 29.6 kPa (4.3 psi). The other component is a large mix of factors primarily comprised of suit factors such as mass, kinematic constraints, and stability as well as system-level components such as harnessing differences between unsuited and suited conditions. Other factors may be unknown and are thus not accounted for. This "other factors" category was calculated by subtracting the metabolic cost of pressure and weight from the total metabolic cost of the suit.

2.4.2 Significant Metabolic Differences

In comparing the metabolic costs of different suited conditions, it is important to define some level of metabolic rate that is deemed practically significant. Because of the limited sample size (n = 6), inferential statistics were not used, therefore statistical significance was not calculated. Based on linear regression of RPE [rating of perceived exertion] and VO_2, RPE increased by 1 unit with an average increase in VO_2 by 2.43 ± 0.53 mL•kg^{-1}•min^{-1}. Although this was the average, it seems that a 2.43 mL•kg^{-1}•min^{-1} change in RPE was not perceptible by most subjects, because the variation in VO_2 greater than 2.43 mL•kg^{-1}•min^{-1} was often seen within a given level of exertion defined by RPE. Within a given RPE for an individual subject, VO_2 variation was often greater than 2.43 mL•kg^{-1}•min^{-1} and could be as much as four times that value depending on the subject (see Figure 7). Based on the linear regression of RPE and VO_2 from VO_2pk testing results for this study and the EWT (n = 8), an increase in RPE occurred with an increase in VO_2 of 4.2 ± 0.5 mL•kg^{-1}•min^{-1}. Through application of these results and discussions within the test team, a change in metabolic rate of 3.5 mL•kg^{-1}•min^{-1} was chosen for practical significance. On average, this was enough to elicit a change in RPE; it also is equivalent to an estimated normal resting metabolic rate and to 10% of the VO_2pk in a subject with a VO_2pk of 35 mL•kg^{-1}•min^{-1} who would be representative of a slightly deconditioned crew member. The average International Space Station (ISS) crew member has a preflight VO_2pk of 43.7 ± 6.1 mL•kg^{-1}•min^{-1} (JSC's Exercise Physiology Lab Database).

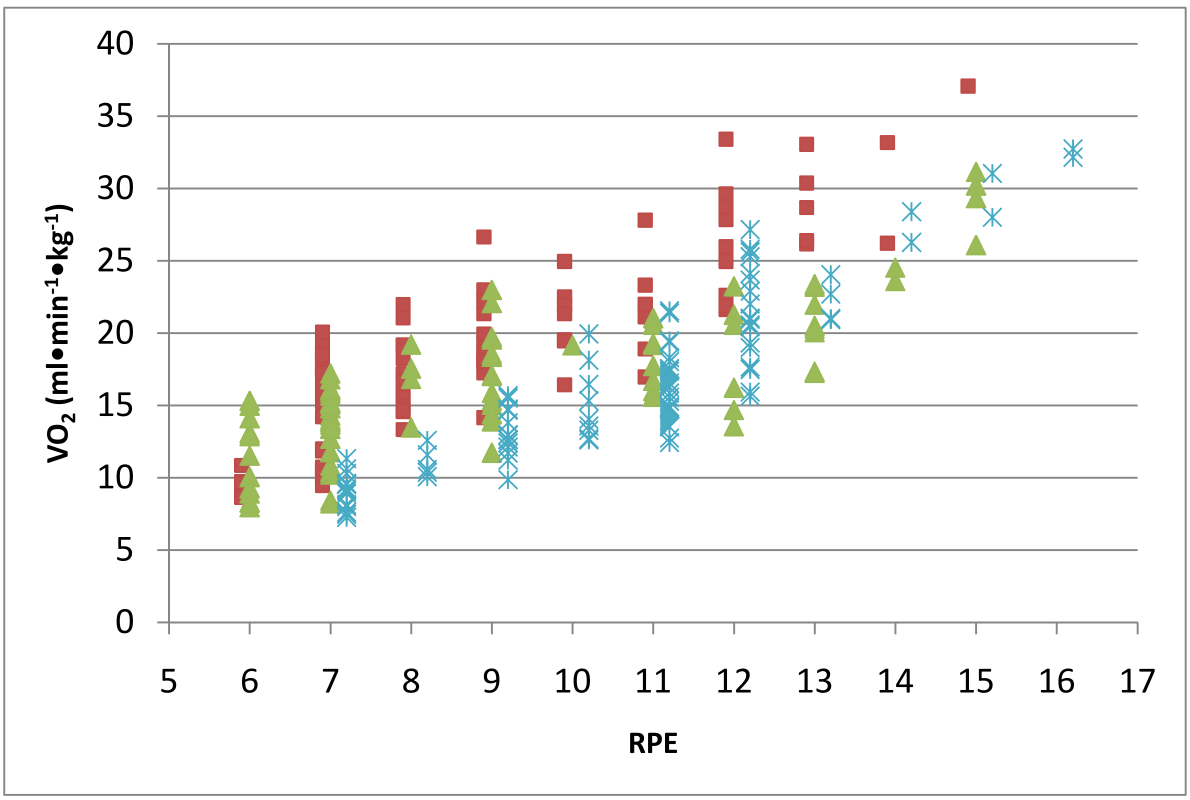

Figure 7. VO_2 vs. RPE for three different representative subjects.

2.4.3 Earth Shirtsleeve Performance Index

It would be desirable to develop a lunar EVA suit that required no more effort to perform a task than the effort required by a person performing the same task on Earth without a suit. The Earth shirtsleeve performance index (ESSPI) is defined as the metabolic cost of a lunar suited task divided by the metabolic cost of performing the same task under Earth shirt-sleeved conditions. The 1-g metabolic cost of an activity (i.e., ambulation in this case) creates a reference point to compare suited data. The ESSPI then provides an index to identify which suited tasks may require the most improvement. To create the 1g reference values, we used linear regression of our 1g data set from the EWT and VO_2pk tests to predict metabolic rates for speeds above 1.34 m•s^{-1}. For speeds below 1.34 m•s^{-1}, we used the American College of Sports Medicine (ACSM) predictive equation (5).

2.5 Biomechanical Data Collection and Analysis

Biomechanical data were collected using a 12-camera motion analysis system (Vicon MX Ultranet hardware, Vicon Nexus software [Vicon Motion Systems Ltd., Oxford Metrics Group, Oxford, U.K.]) and four strain-gauge force plates (AMTI, Watertown, MA). The force data were then processed and analyzed using customized MATLAB (The MathWorks, Inc., Natick, MA) computer programs. Data were sampled during 30 full, consistent strides during each stage of testing.

Ground reaction forces were collected using 46.2- × 50.8-cm force plates, mounted to each corner inside the treadmill and underneath the treadmill belt support plate (Figure 8). The signal was collected at 1,000 Hz over 30 gait cycles at varying speeds, pressures, and simulated suit weights and then stored for subsequent analysis. The vertical components of each of the four force-plates were resolved into one vertical component and summed together for each of the 30 gait cycles. For all trials, in each of the conditions, the peak vertical force was determined using customized MATLAB computer code over the 30 gait cycles.

Three-dimensional trajectories of retro-reflective markers, placed at approximate anatomical landmarks on the MKIII suit, were collected at 100 Hz (Vicon, Oxford Metrics Group, Oxford, U.K.) to determine the displacement of segments of the suit. These trajectories were then filtered, processed, and reduced to the three-dimensional angular displacement of the three lower extremity joints during locomotion employing customized computer code. This information was used for subsequent analysis to describe the kinematics of the MKIII suit during treadmill ambulation at varying suit pressures and weights.

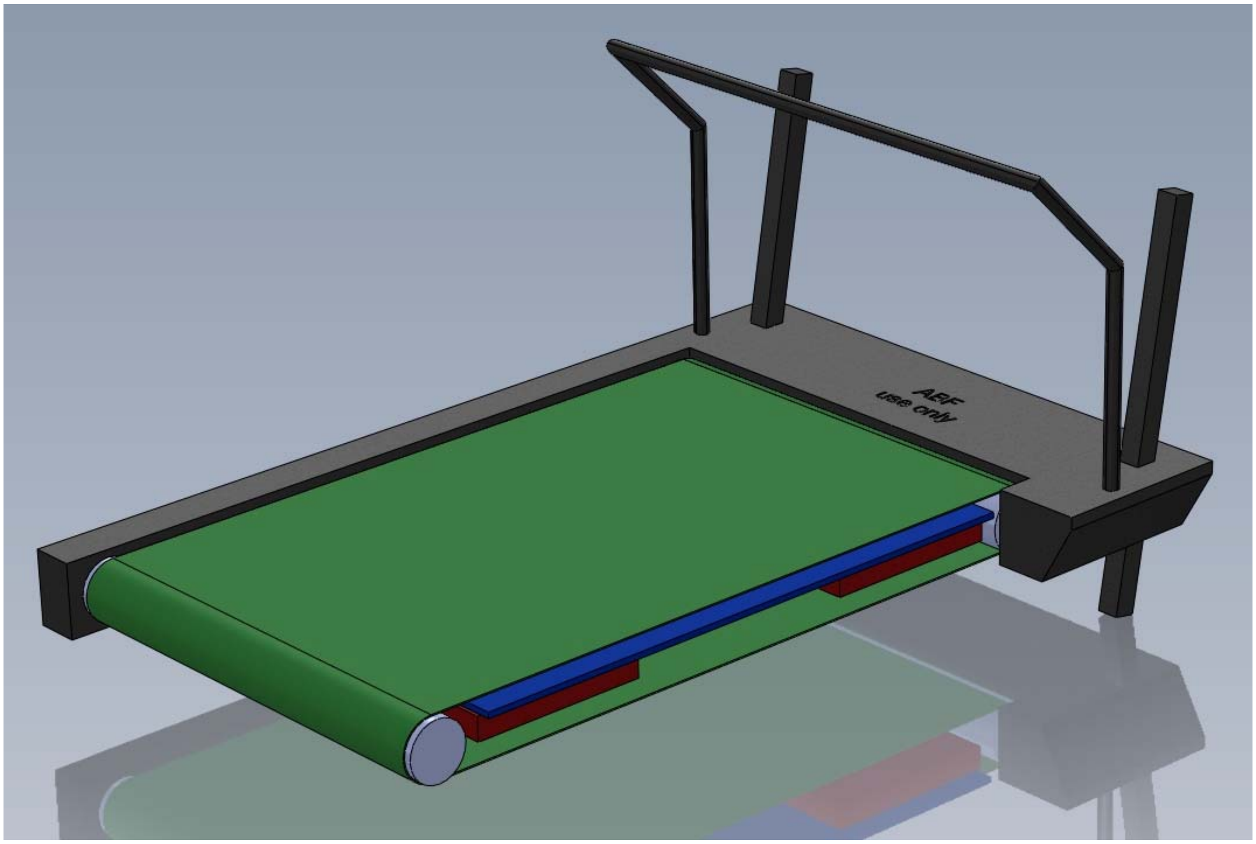

Figure 8. Four force plates (red boxes) were mounted to each corner support structure of the treadmill underneath the treadmill belt

The motion analysis system (a modified Plug-in-Gait (Vicon Motion Systems Ltd., Oxford Metrics Group, Oxford, U.K.) marker set (see figures 9 and 10), attached to each body segment of the subjects) was used to record the three-dimensional trajectories of 51 reflective markers. The three-dimensional trajectory data were reduced and analyzed using customized MATLAB computer programs to provide selected kinematic and temporal spatial characteristics of suited human locomotion.

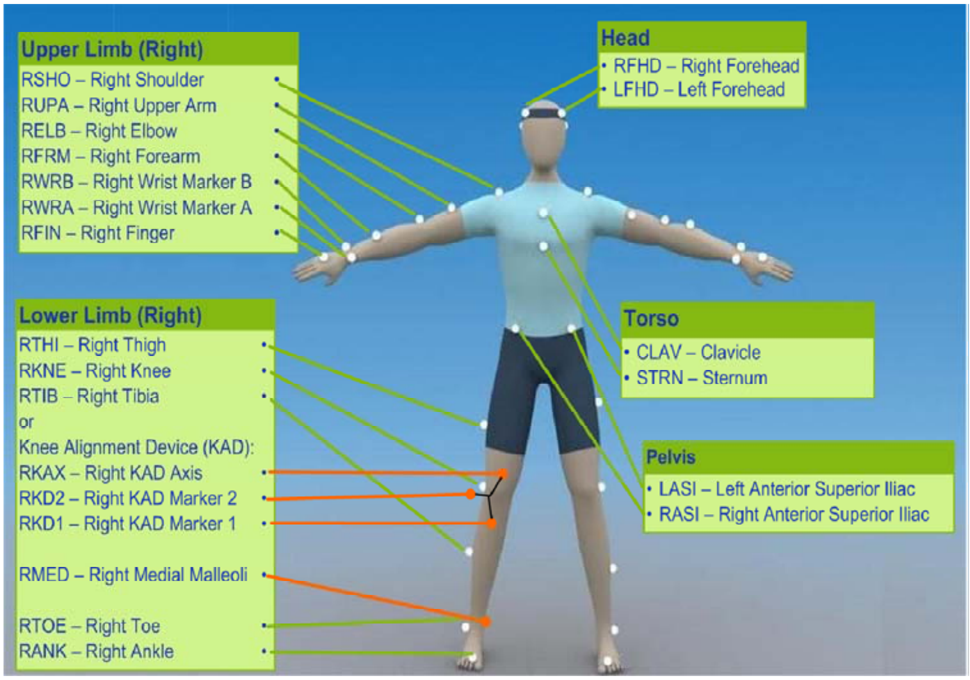

Figure 9. Anterior view of Plug-in-Gait marker set.

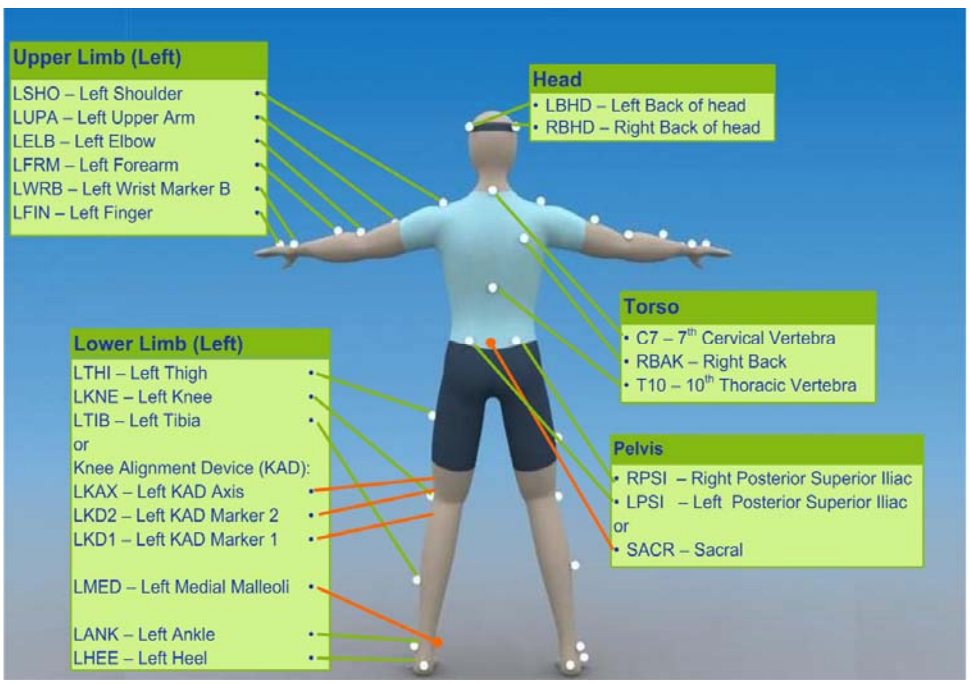

Figure 10. Posterior view of Plug-in-Gait marker set.

In movements such as locomotion, the motions of segments are cyclic in nature. More specifically, walking is the periodic movement of each foot from one position of support to the next. For walking, one stride (or cycle) is defined as the distance traveled by a person from one heel strike to the next heel strike on the same side. For analysis, each trial was subdivided into gait cycles. Information from each gait cycle was extracted and averaged assuming that constant gait was maintained.

2.6 Subjective Data Collection and Analysis

2.6.1 Self-reported Subjective Data

The following subjective ratings were recorded at the end of each testing condition:

- The gravity compensation and performance scale (GCPS) was used to assess the level of compensation to maintain performance in reduced gravity as compared to performance achieved while unsuited at 1-g (1).
- RPE was used to gauge how much effort subjects felt they must exert to complete each condition (6).
- The Corlett and Bishop body part discomfort scale was used to characterize discomfort at different body locations (7).
- Thermal comfort was assessed to determine the subjective thermal comfort of the subject, and to determine whether any changes were necessary to improve the thermal comfort of the subject during testing. Thermal comfort was assessed using the Bedford scale (8).

Additional information on each of these scales is included in Appendix B of this document. In addition, RPE will be used in conjunction with GCPS to develop predictive models for metabolic rate with the intent that these subjective factors can be used in other lunar analog environments (e.g., underwater analogs and parabolic flight where direct measures of metabolic rate are currently not possible). Discomfort and thermal comfort were both primarily used for test termination criteria as well as to provide feedback to the test team about test hardware, conditions, and length of trials. Discomfort and thermal data will not be discussed in this report.

2.6.2 Significant Subjective Differences

In comparing the subjective ratings of different conditions, it is important to define some level of change that is deemed practically significant. Because of the limited sample size (n = 6), inferential statistics were not used; therefore, statistical significance was not calculated. For these analyses, a change in RPE of 2 was chosen for practical significance. RPE changes of one unit are approximately at the level of practical significance for VO_2, but, because RPE is a whole number scale, it would take a change >1 to see practically significant differences in metabolic rate. Further, the description of VO_2 variability within a given RPE (Figure 7) demonstrated the large VO_2 variability for a given RPE.

GCPS is not a continuously linear scale as is RPE. Therefore, it is more complicated to assign a simple level of practical significance to changes in GCPS. It is reasonable to define a range of GCPS, where changes within the range are of interest, but would not be considered to be practically significant. Using this breakdown, we selected a GCPS category of 1 to 3 as “ideal,” 4 as “acceptable,” 5 to 6 as “modifications warranted,” 7 to 9 as “modifications required,” and 10 as “unable to complete the task.” For some discussions, a value of 10 was lumped in with the 7 to 9 range as these would all be considered “unacceptable” performance. Full consensus within the team was not achieved on whether a value of 4 is more associated with the “ideal” range or the “modifications warranted” range. For the modeling data discussed in the following sections, a value of 4 was included in the “modifications warranted” category, but for direct interpretation of the results, we have chosen a value of 4 to stand alone as its own category. Therefore, a level of practical significance for GCPS is one in which the value changes to a different category.

2.7 Imaging

Photographic data were collected after completion of each testing run if human-suit interactions were unfavorable or resulted in skin or musculoskeletal abnormalities. This information is available to the JSC Space Medicine Division and EVA suit engineers. During all suited tests, a digital video camera captured video of the subject in the sagittal plane as well as auditory comments of the crew member and test team. During all unsuited tests, video was captured without audio.

3 RESULTS AND DISCUSSION

The results of IST-1 and their implications are discussed in this section, which is separated into subsections corresponding to the test objectives described in Section 1.1. For each test objective, the results of the analyses performed to date are described; the potential implications of these results are discussed with respect to EVA suit requirements, design, and concepts of operations; and the suggestions for further analyses or testing to meet the test objectives are described.

Before specific analysis of objectives is addressed, results pertinent to the interpretation of the data include the speed selection of individual subjects and alignment of the gimbal axes of rotation with the system CG.

Preferred Transition Speeds

Table 3 describes the unsuited PTS at lunar gravity. Individual subject speeds were based on the PTS described in Table 2. The results were similar to those seen in the EWT (1) in that the PTS did not agree with a predicted Froude number of 0.5 (9).

Table 3. Unsuited PTS at Lunar Gravity

Subject	1/6-g Unsuited		
	PTS ($m \cdot s^{-1}$)	PTS (mph)	Froude
1	1.52	3.4	1.56
2	1.43	3.2	1.28
3	1.34	3.0	1.29
4	1.30	2.9	1.00
5	1.56	3.5	1.38
6	1.65	3.7	1.67
Mean ± SD	1.47 ± 0.14	3.3 ± 0.30	1.36 ± 0.23

Location of System Center of Gravity

When assessing CG effects, the POGO system posed potential problems in two primary areas: The first was that the system CG may not line up with the gimbal axes of rotation, and the second was that the system CG may differ from the subject's CG. Regarding the first potential problem, the location of the total system CG from the gimbal center of rotation averaged 1.24 ± 0.95 cm forward and 1.39 ± 1.22 cm low. As seen in Figure 11, five of six subjects selected this slight misalignment between the system CG and gimbal center of rotation that was forward and low with the remaining subject just slightly higher than 0 and forward as well. Results of the second potential problem were discussed in the EWT final report, which states that the total system CG, based on a computer-aided design (CAD) model of the gimbal support structure, MKIII suit, and standard (182.9 cm, 81.6 kg) subject, differed from the subject's CG by11.0 cm aft and 20.1 cm high when compared to the CG of a standard 182.9 cm, 81.6 kg CAD modeled subject (1).

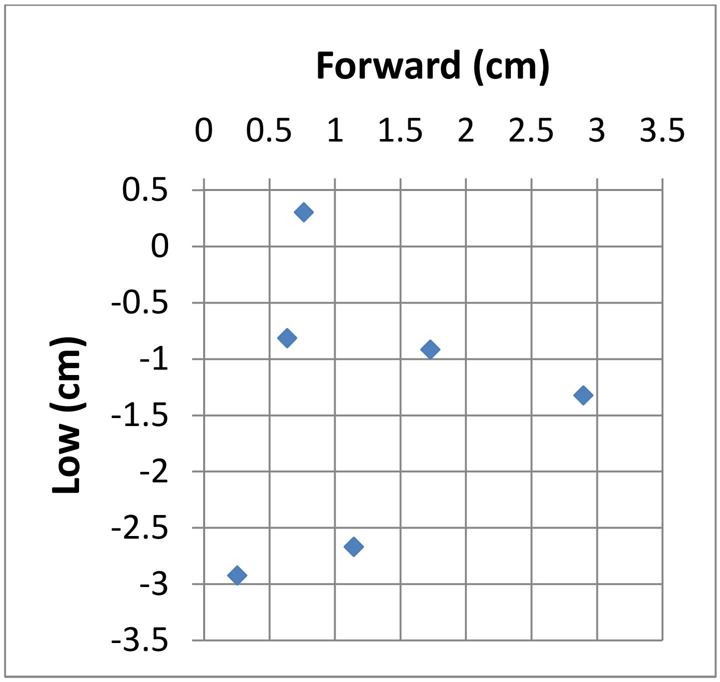

Figure 11. Total system CG location in relation to gimbal center of rotation.

3.1 Test Objective 1: Contributions of Weight, Mass, Pressure, and Suit Kinematics to Metabolic Cost of MKIII Suit POGO Configuration

Test Objective 1 was to identify the individual contributions of weight, inertial mass, pressure, and suit kinematics to the overall metabolic cost of the MKIII suit in its POGO configuration (121 kg [265 lb] including mass of portable life support system (PLSS) mockup and gimbal, 29.6 kPa [4.3 psi]) during lunar ambulation.

The individual contributions of weight and pressure along with the combination of remaining components including mass, suit kinematics, stability, and system harness differences to the overall metabolic cost of the MKIII suit in POGO configuration are shown in Figure 12 (absolute metabolic cost) and Figure 13 (percentage metabolic cost). The methods for calculating individual contributions are described in Section 2.4.1. In all cases, the baseline unsuited component accounted for the greatest percentage of total metabolic cost. The figures show that the overall metabolic cost of the MKIII suit in POGO configuration was considered to be the same for speeds 1 to 3 at 7.3 to 7.6 mL•kg^{-1}•min^{-1} and then increased to 7.9, 9.4, and 11.4 mL•kg^{-1}•min^{-1} at speeds 4, 5, and 6 respectively. Although the metabolic cost of the suit increased in absolute terms, it decreased as a percentage of total metabolic rate as speed increased. Differences caused by "Other

Suit/System Factors" were most prominent at speeds 1 and 6. At speed 1, the additional weight seemed to positively affect the metabolic rate; but at the slow speed, the subject may have experienced greater inertial effects as well as more cumbersome suit kinematic programming. At speed 6, differences caused by "Other Suit/ System Factors" may have been due to the greater range of motion (ROM) in all joints leading to more travel and, thus, increased force required to stop the rotating components of the suit.

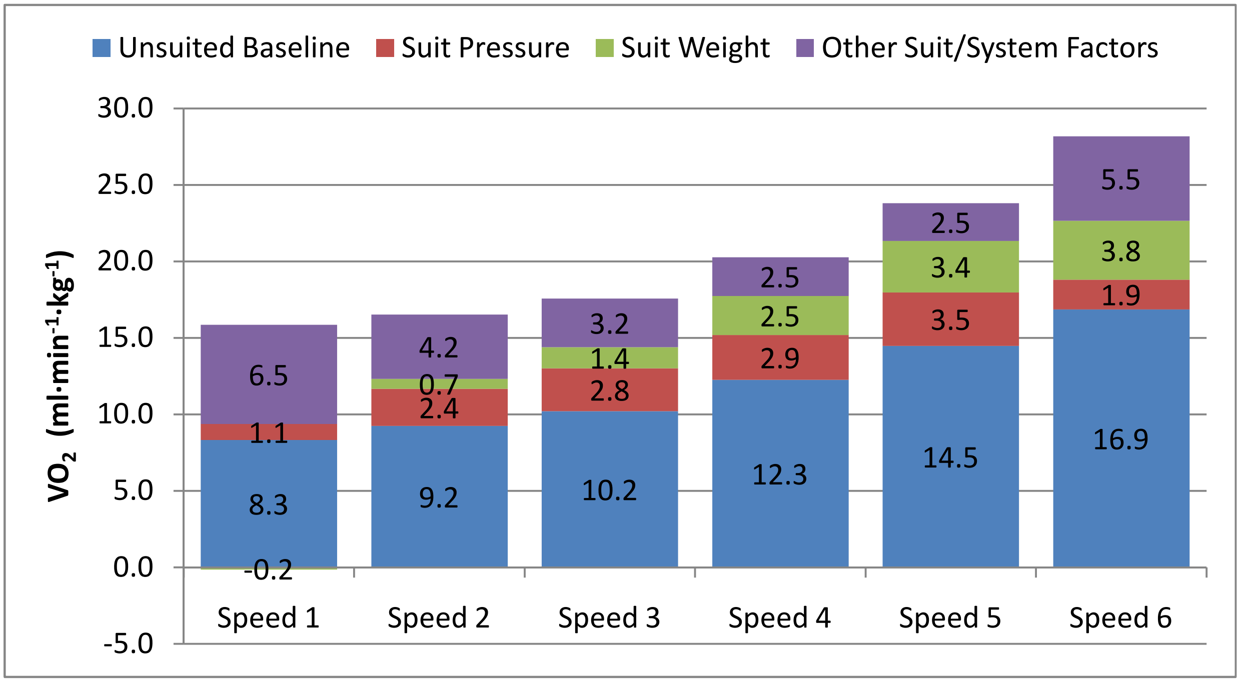

Figure 12. Model for absolute metabolic cost of components comprising suited locomotion for the MKIII suit in POGO configuration in lunar gravity.

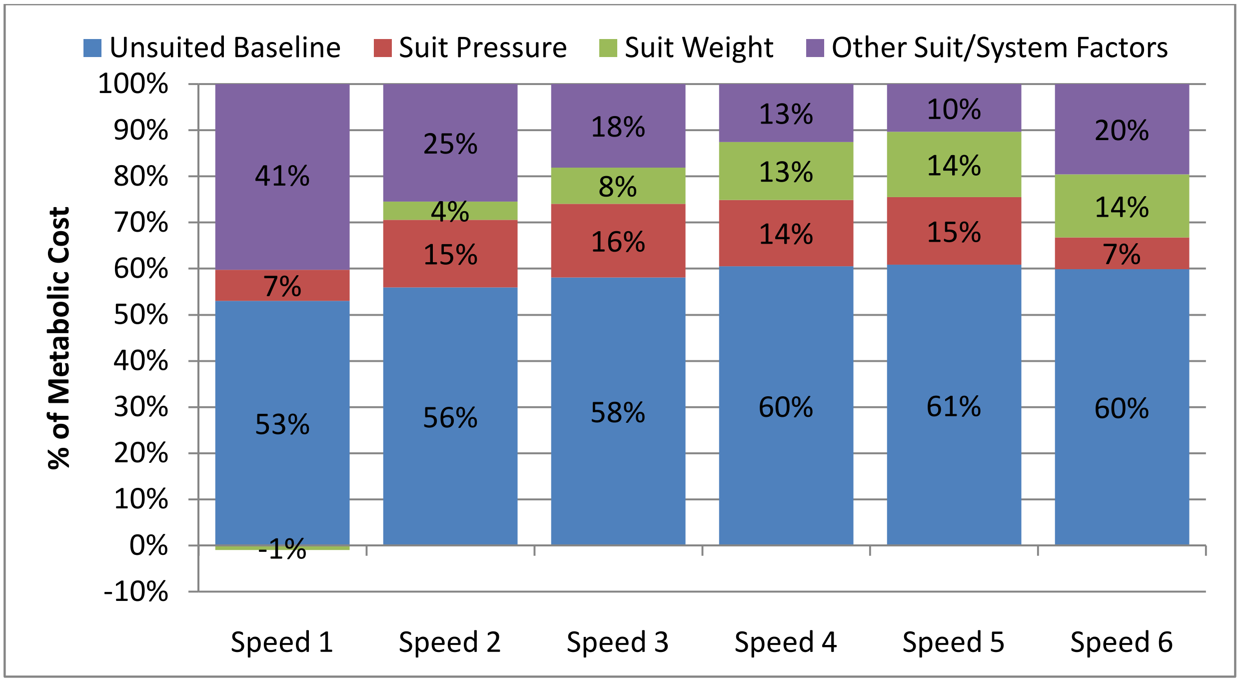

Figure 13. Model for percentage metabolic cost of components comprising suited locomotion for the MKIII suit in POGO configuration in lunar gravity.

The unsuited baseline metabolic cost was consistently the largest component of the model at about 60% of total metabolic cost with the other components variable. The absolute metabolic cost of pressure-volume work at 29.6 kPa (4.3 psi) slowly increased with increasing speeds, but did drop at the fastest speed. For speeds 2 to 5, the percentage contribution of pressure-volume work accounted for about 15% of the total metabolic cost. It is not understood why the pressure-volume work cost was lower at the slowest and fastest speeds, but these speeds may be outside of the optimal locomotion envelope for suited subjects.

The metabolic cost of weight steadily increased as speed increased, but the proportion of metabolic cost plateaued at 14%. As the metabolic cost of weight increased, the cost of the other factors decreased, indicating there are variable trends among the other factors.

Future tests will determine the individual contributions of these remaining components using the MKIII and other EVA suit concepts. The "Other Suit/System Factors" can be broken done further to include mass and possibly suit kinematic constraints. In addition, various inter-relationships and coupling factors may be present in untested combinations of these variables and may need to be tested. By understanding these individual factors, we will be able to provide specific recommendations for suit design requirements, EVA mission planning, and overall consumables packaging.

Finally, the metabolic cost of the suit did not change significantly (as defined in Section 2.4.2) over the expected range of nominal lunar locomotion speeds (≤1.5 m•s^{-1}).

3.2 Test Objective 2: To Quantify the Effects of the Following Factors on Suited and/or Unsuited Metabolic Rate, Biomechanics, and Subjective Ratings during Level-ground Ambulation at Varied Speeds

a. Suited – varied suit pressure at constant offload, mass, and CG
b. Suited – varied suit offload (weight) at constant pressure, mass, and CG
c. Unsuited – varied offload (weight) at constant mass and CG
d. Unsuited – varied mass at constant offload and CG

3.2.1 Effect of Varied Pressure at Constant Offload and Mass on Suited Human Performance

Metabolic Rate Findings

Variation in suit pressure at simulated lunar gravity did not significantly affect metabolic rate (see Figure 14). The largest difference was between 6.9 kPa (1.0 psi) and 34.5 kPa (5.0 psi), with the difference ranging from 0 to 3.0 mL•kg^{-1}•min^{-1} across the range of speeds.

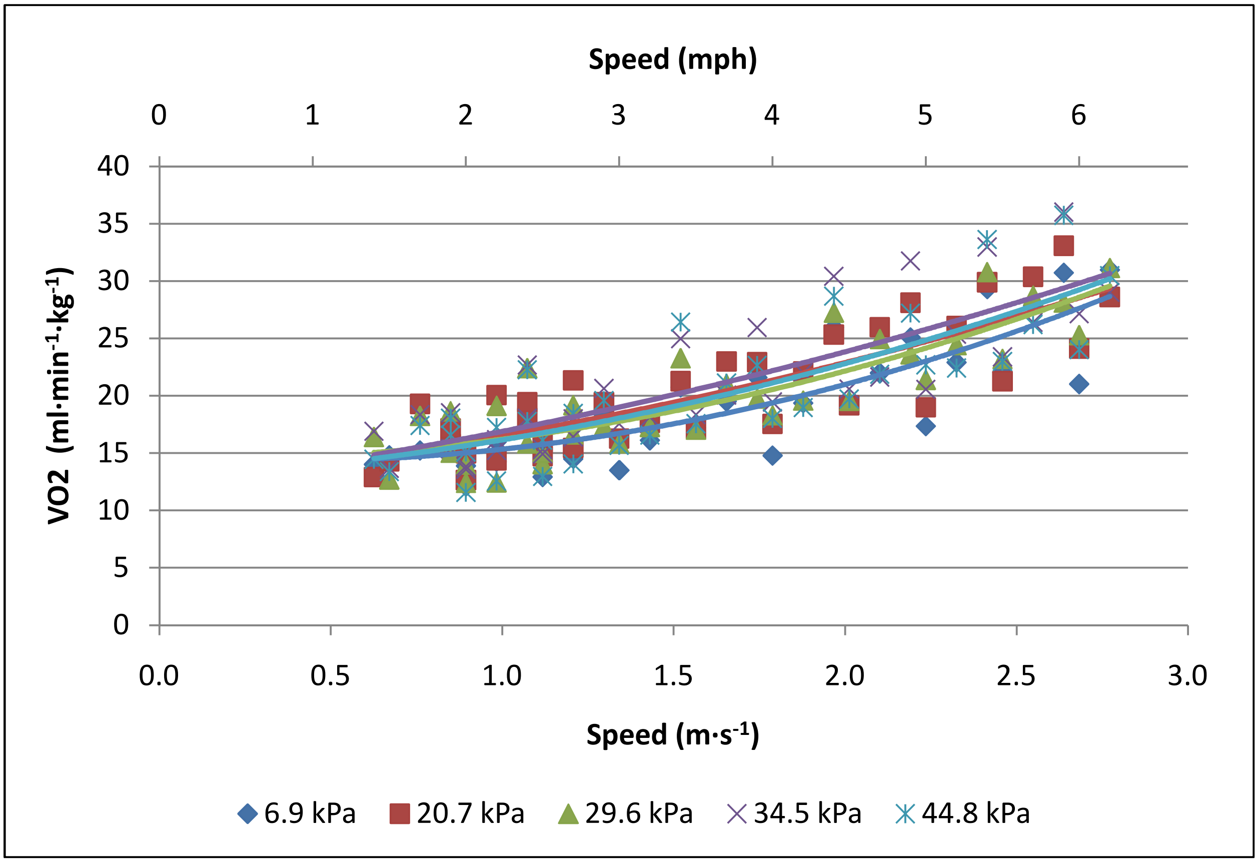

Figure 14. Metabolic rate vs. speed at different suit pressures during suited (121-kg) locomotion at lunar gravity.

While the average difference was not significant (<3.5 mL•kg^{-1}•min^{-1}), there was some variation between individual subject results ranging from higher metabolic rates at higher pressures (Figure 15A) to higher metabolic rates at lower pressures (Figure 15B) to almost no variation between pressures (Figure 15C) to results very similar to the overall mean (Figure 15D). The only truly consistent findings was that the 34.5-kPa (5.0-psi) trials led to the highest average metabolic rate in five of the six subjects and the 6.9-kPa (1.0-psi) trials led to the lowest metabolic rate in four of the six subjects.

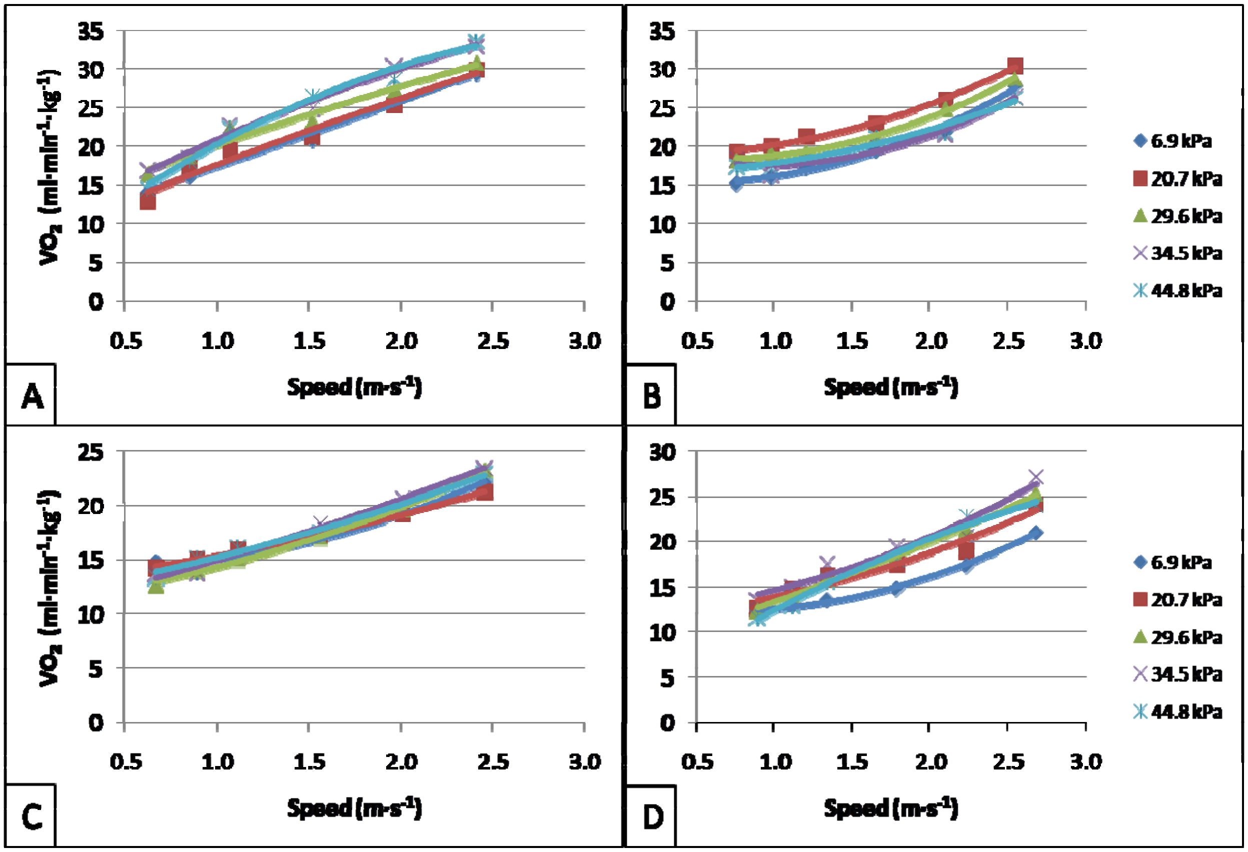

Figure 15. Individual subject (A–D) metabolic rate responses to varied pressures at increased speeds.

Initially, there was a trend towards smaller subjects having lower metabolic rates at lower suit pressures and larger subjects having lower metabolic rates at higher suit pressures; but while this held true for our first two subjects, it did not continue for the remaining four subjects, nor was it supported by any significant differences in biomechanics results. Carr and Newman, in a comprehensive review of past studies, showed how running might be more efficient than walking with pressure as one of the components of their model explaining this difference (2).

Our initial hypothesis was that larger subjects could bend the suit legs with less effort because of the mechanical advantage of larger leg bending moments and, possibly, greater muscular strength. During the stance phase (the portion of a stride where the foot contacts the ground), increased strength and mechanical advantage would allow these subjects to bend the knee more and store more energy elastically in the suit. The pressurized suit leg would essentially behave as an inflated beam and, once deflected, would have a tendency to recoil back to neutral position, with the recoil force being proportional to the inflation pressure. The degree of energy recovery would be proportional to the deflection of the knee and the suit pressure. This was a controversial hypothesis, however, with disagreement based on the conservation of energy theorem (i.e., the suit cannot add energy to the subject that was not already put into the suit by the subject). Therefore, the subject still has to perform extra metabolic work to get extra mechanical energy back from the suit.

The knee joint of the MKIII has been found to maintain almost a constant volume, indicating that energy recovery, because of the inflated beam theory, is unlikely. Further analysis of biomechanics, anthropometry, and subject strength coupled with a larger subject pool would be needed to quantitatively evaluate this trend. Evaluation of another suit design that does not have a constant volume knee joint is recommended.

Figure 16 shows there was very little variation in metabolic rate as a function of pressure for six different ambulation speeds, suggesting that metabolic costs are more related to ambulation speed than to suit pressure. A drop in metabolic rate, from 20.7 kPa to 6.9 kPa, was experienced, but it did not meet our significance criteria. This drop demonstrated there was an increase in metabolic rate because of pressurization of the suit; but when an operationally relevant pressure (one that could sustain life in space) was achieved, there was little difference from 20.7 to 44.8 kPa.

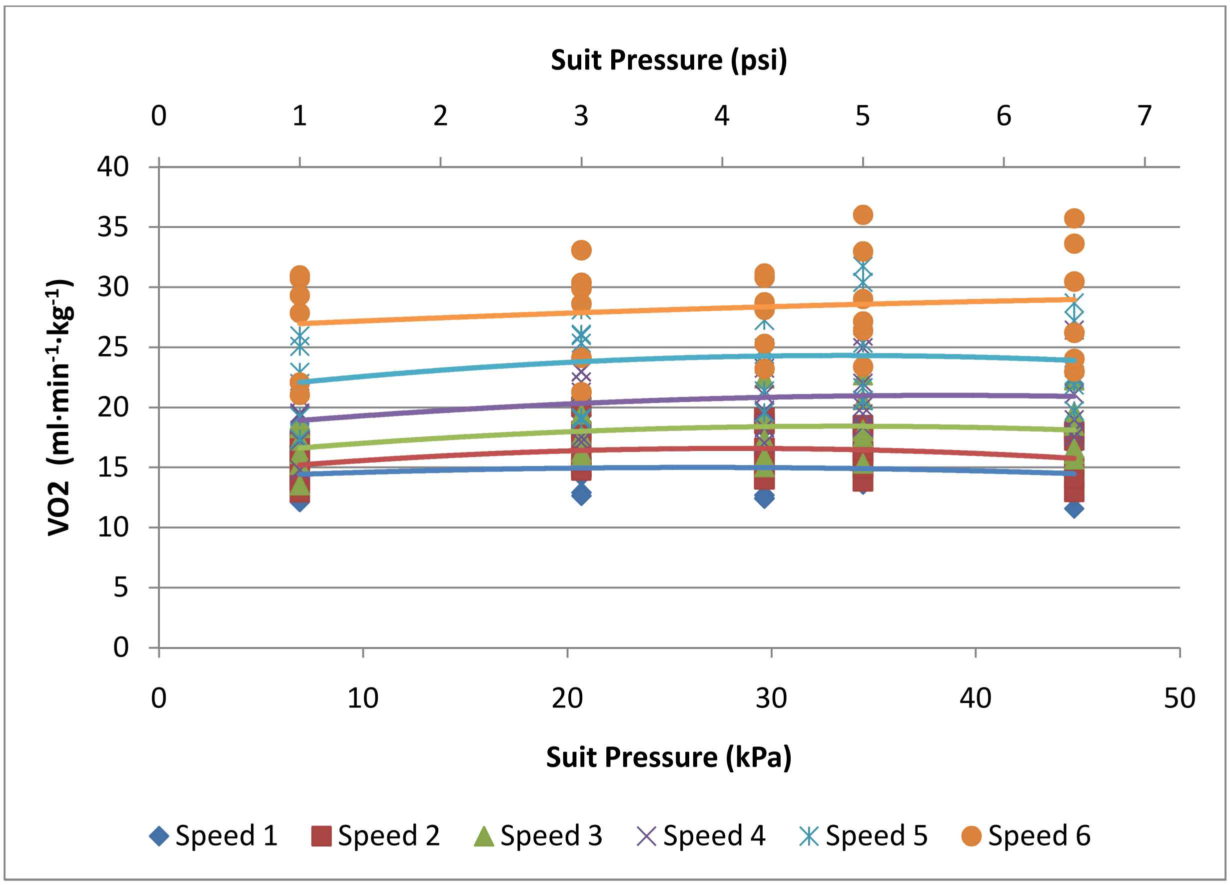

Figure 16. Metabolic rates within speeds at different suit pressures for suited locomotion at the 121-kg suit mass at lunar gravity

Overall, suit pressurization increases metabolic rate, but varying suit pressure within an operationally relevant range (20.7 – 44.8 kPa) minimally influenced the metabolic rate for the group as a whole. However, there was some evidence that pressure may affect individual subjects differently during level-ground ambulation, as shown in the variability in individual responses (Figure 15). It is important to note that this test was limited to ambulation and does not imply that suit pressure would not significantly affect crew members performing upper body and hand intensive exploration tasks.

Subjective Findings

Subjective findings showed similar trends to the metabolic rate. Little variation was noted in either RPE or GCPS ratings between the tested suit pressures as shown in Figure 17 and Figure 18, respectively. RPE increased with speed, as expected, and closely mirrored the metabolic rate findings as seen in Figure 14. GCPS ratings trended towards increasing with speed, but were generally between the ideal range of ≤3 and the acceptable range of ≤4 for speeds 1 to 5, which encompasses the range of nominal lunar suited ambulation speeds of <1.5 m•s^{-1}. GCPS ratings were all ≤4 for speeds 1 to 5. Only speed 6 had GCPS ratings above acceptable, likely because of the difficulty of running at this speed in the MKIII for some subjects.

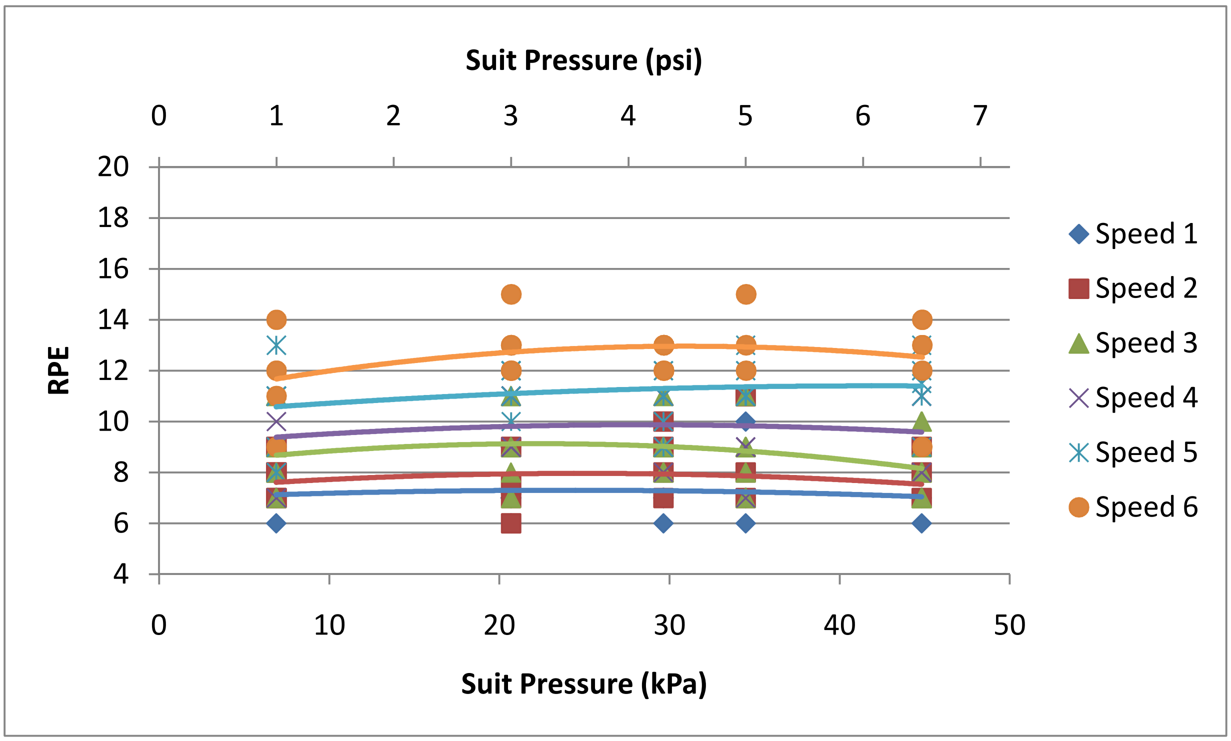

Figure 17. RPE at varied pressures for suited locomotion at the 121-kg suit mass in lunar gravity.

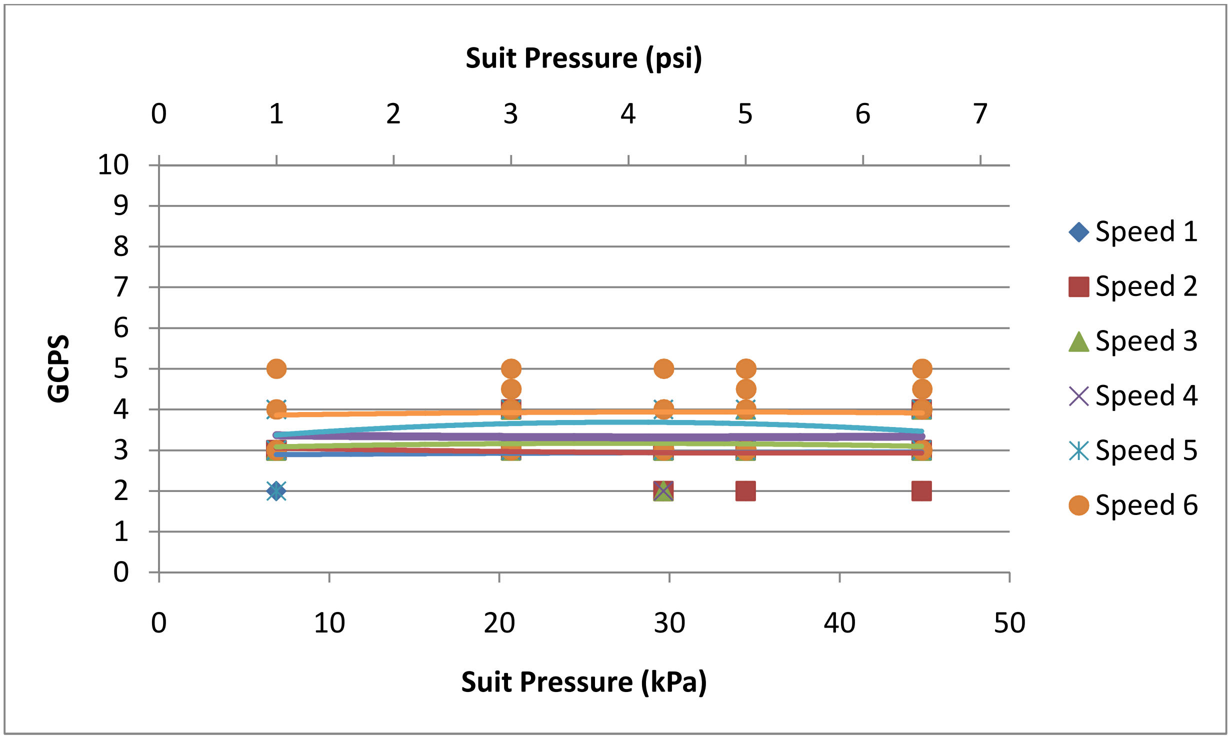

Figure 18. GCPS ratings at varied pressures for suited locomotion at the 121-kg suit mass in lunar gravity.

Biomechanics Findings

Changes in suit pressure exhibited minimal changes in selected biomechanical variables. Mean peak ground reaction force (GRF) increased with increasing speed, but showed no observable trends with change in pressure. Temporal spatial gait parameters, including percentage of stance time, step width, and cadence, demonstrated no observable changes with changes in suit pressure. The joint ranges of motion for the hip, knee, and ankle showed increases with increasing speed, similar to GRF, but there was no consistent effect in varying pressure (Figure 19-Figure 21).

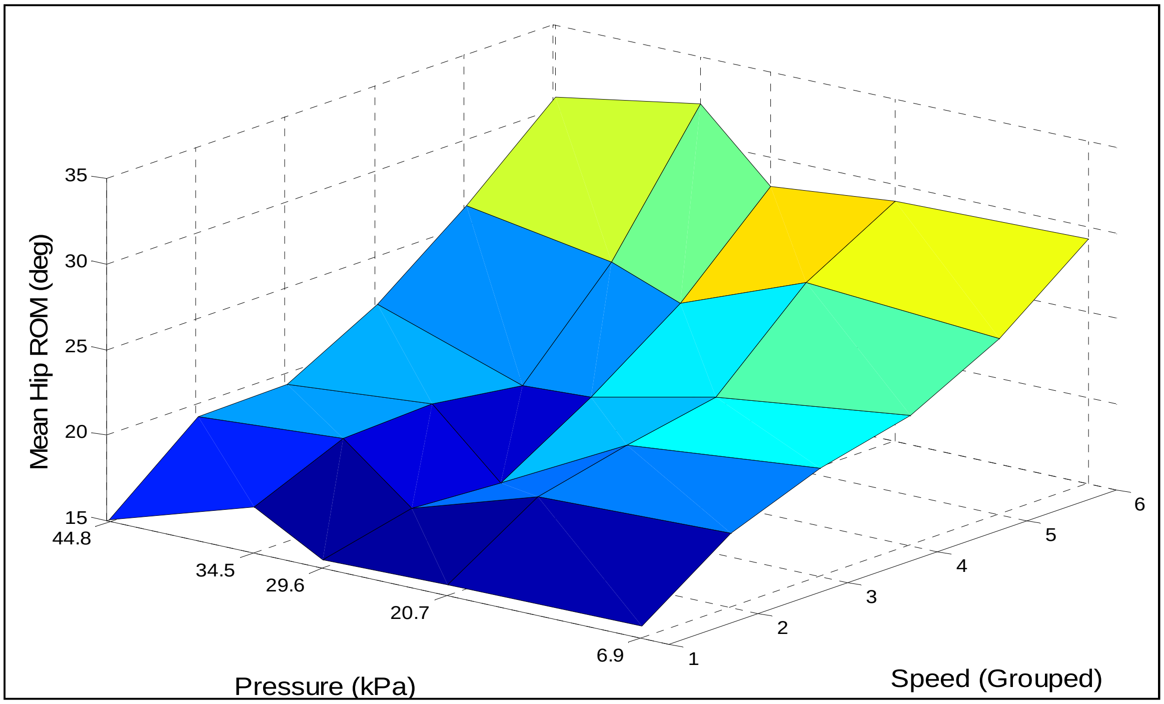

Figure 19. Hip ROM as a function of suit pressure and speed. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (greens and blues) demonstrate the lower values observed.

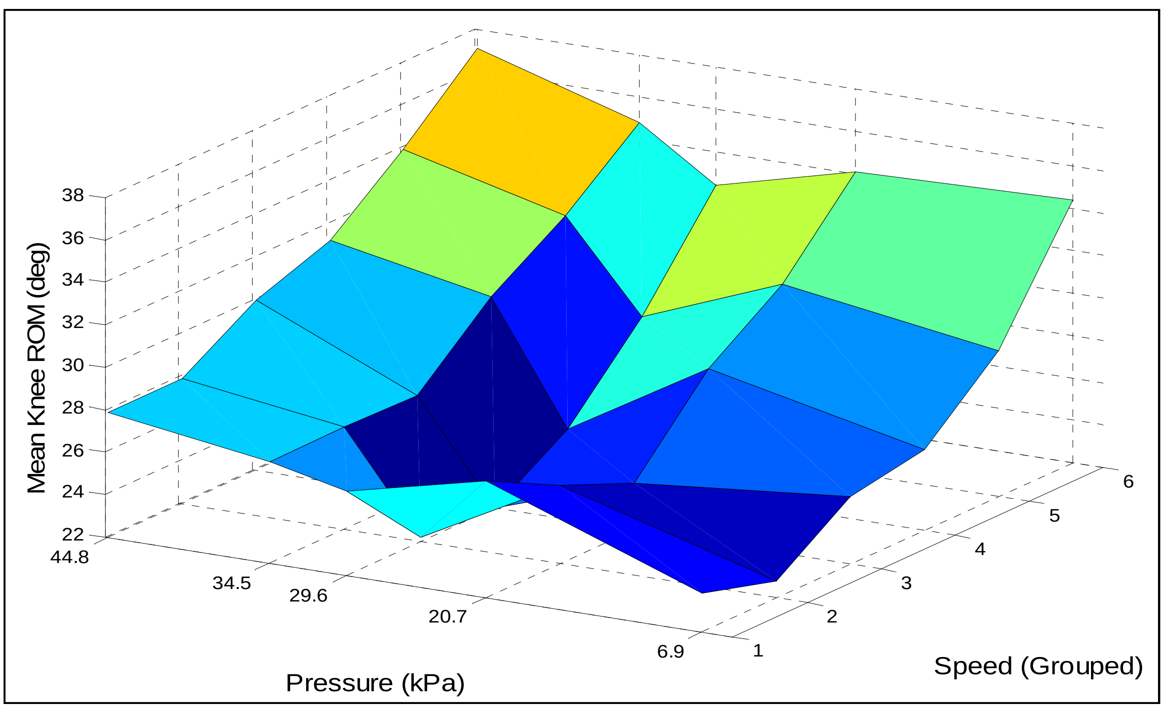

Figure 20. Knee ROM as a function of suit pressure and speed. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (greens and blues) demonstrate the lower values observed.

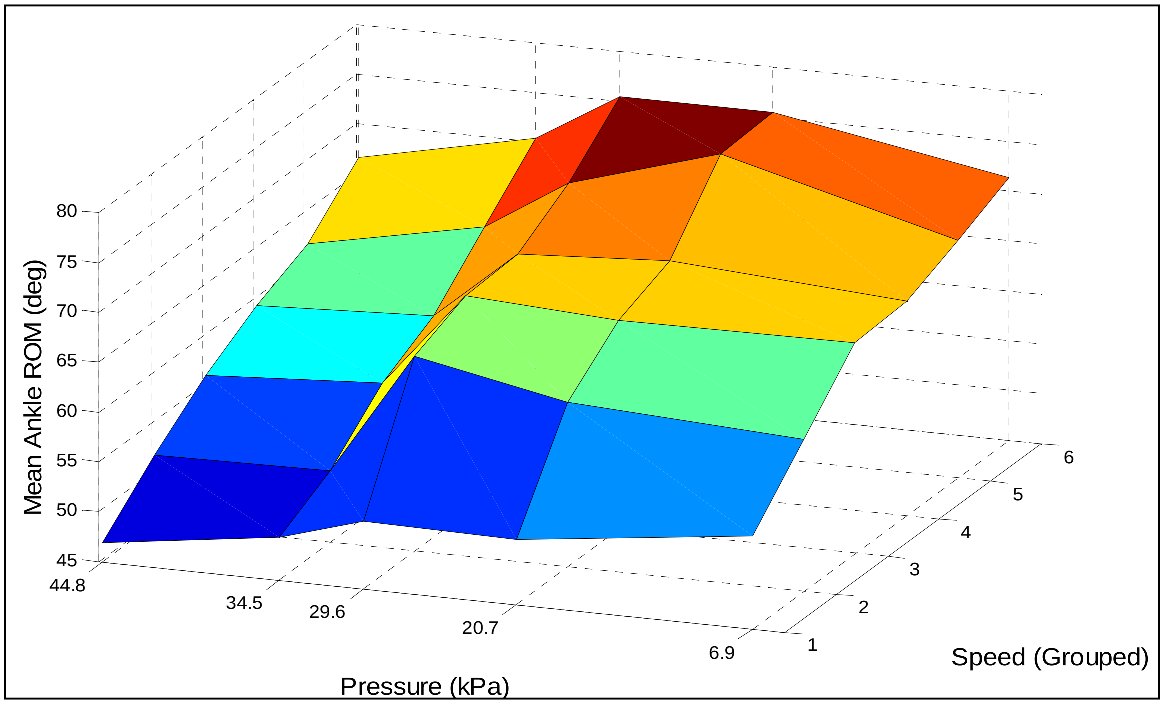

Figure 21. Ankle ROM as a function of suit pressure and speed. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (greens and blues) demonstrate the lower values observed.

Further examination of the joint ROM data demonstrates an anomaly that occurs at 29.6 kPa pressure. The three-dimensional surface plots for the joint ROM for both the hip and the knee display a "trough" at 29.6 kPa for all speeds. However, the ankle joint ROM shows a "ridge" at 29.6 kPa for all speeds. More specifically, the ankle joint is being used to create larger ranges of motion while there is a decrease in ROM for the other joints as observed at this pressure across all speeds. This finding suggests something is altering the gait kinematics at this pressure. This irregularity may be because of several factors including, but not limited to, POGO offloading mechanics, suit fit, experimental design, and/or suit kinematics at that pressure. Further study is warranted to understand this phenomenon. Given that the scope of the test did not allow for isolating all selected variables of interest, it is difficult to ascertain the cause of this trend observed in the data.

Overall, these findings suggest that as suit pressure increases, the average joint ROM in the hip, knee, and ankle does not change significantly, which supports the observation that metabolic rate is essentially unchanged by suit pressure. Different suit designs with different joint designs and sequencing might be affected differently by suit pressure. For example, an entirely soft suit, such as the advanced crew escape suit (ACES), would, when compared to the MKIII, likely have a very different joint ROM and metabolic cost in response to increasing pressure.

3.2.2 Effect of Varied Offload (Weight) at Constant Mass and Constant Suit Pressure on Suited and Unsuited Human Performance

Metabolic Findings

Figure 22 shows the relationship between metabolic rate and ambulation speeds for subjects in the MKIII at a constant suit mass of 121 kg and a suit pressure (29.6 kPa) at varied gravity levels. The difference in average metabolic rate between the lowest and the highest gravity levels for speeds less than 1.0 m•s^{-1} was 2.03 mL•kg^{-1}•min^{-1}, which was not significant (≤3.5 mL•kg^{-1}•min^{-1}). As speed increased beyond 1.0 m•s^{-1}, the differences between gravity levels became more apparent. Between any two adjacent gravity levels, the differences were not significant until running speeds of 2.0 m•s^{-1} or greater, where differences between 0.17-g and 0.22-g and 0.27-g and 0.32-g were highest. At speeds above 1.0 m•s^{-1}, the differences in gravity level became significant. The difference between the lowest and the highest gravity level varies from approximately 7 mL•kg^{-1}•min^{-1} at speeds between 1.0 and 1.5 m•s^{-1} up to approximately 14 mL•kg^{-1}•min^{-1} at speeds between 1.5 and 2.0 m•s^{-1}.

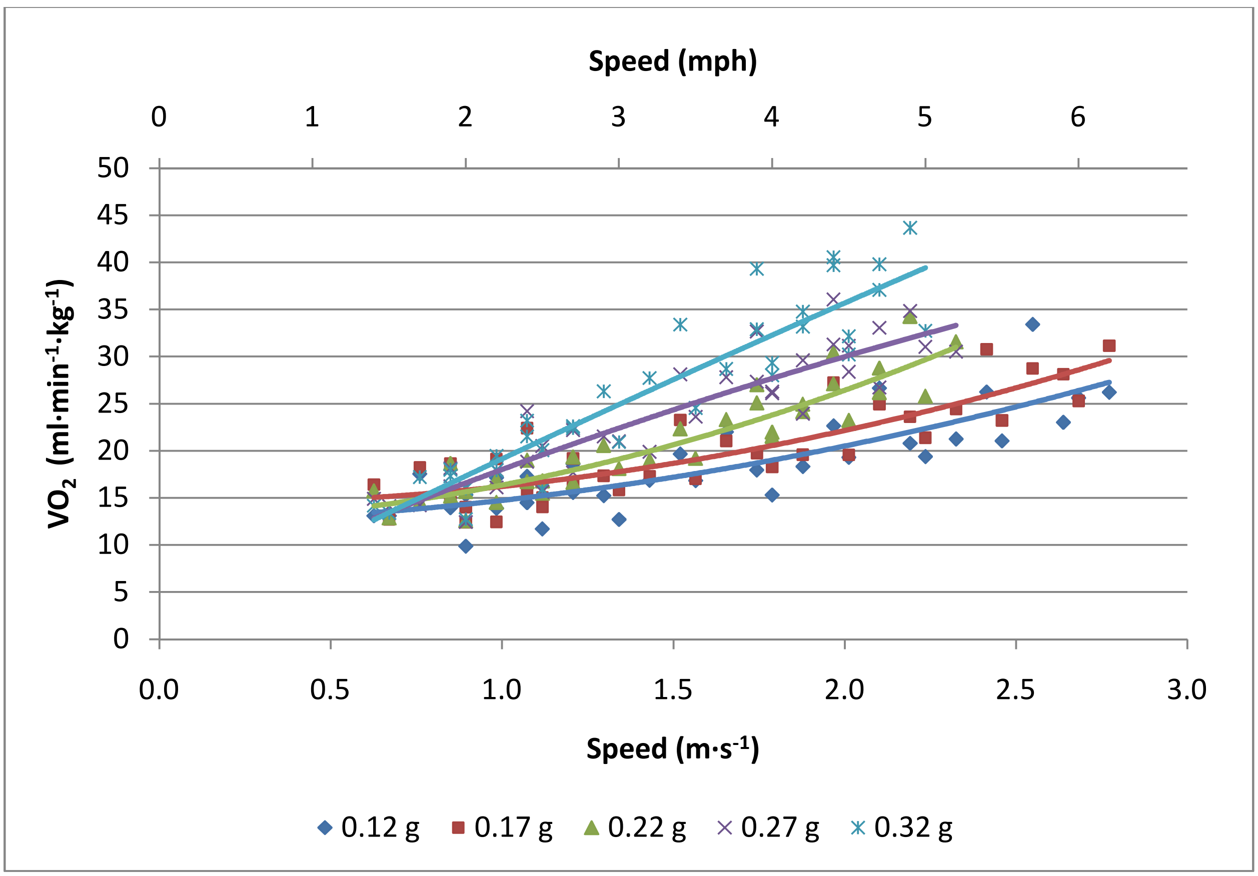

Figure 22. Metabolic rate vs. speed at different gravity levels during suited locomotion at a constant mass (121 kg) and pressure (29.6 kPa)

To better understand the suit-related factors that increase metabolic rate with increasing weight, we compared the suited metabolic rates to the metabolic rates of weight-matched unsuited subjects.

Figure 23 shows the relationship between metabolic rate and gravity level, or TGAW, for five different ambulation speeds with suited subjects. The effect of increasing weight is most apparent at the higher speeds that would be seen during site-to-site translation or during an emergency walkback. These differences were almost negligible at the two lowest speeds, which would be associated with the intra-site translation speeds most likely to be seen during a lunar EVA.

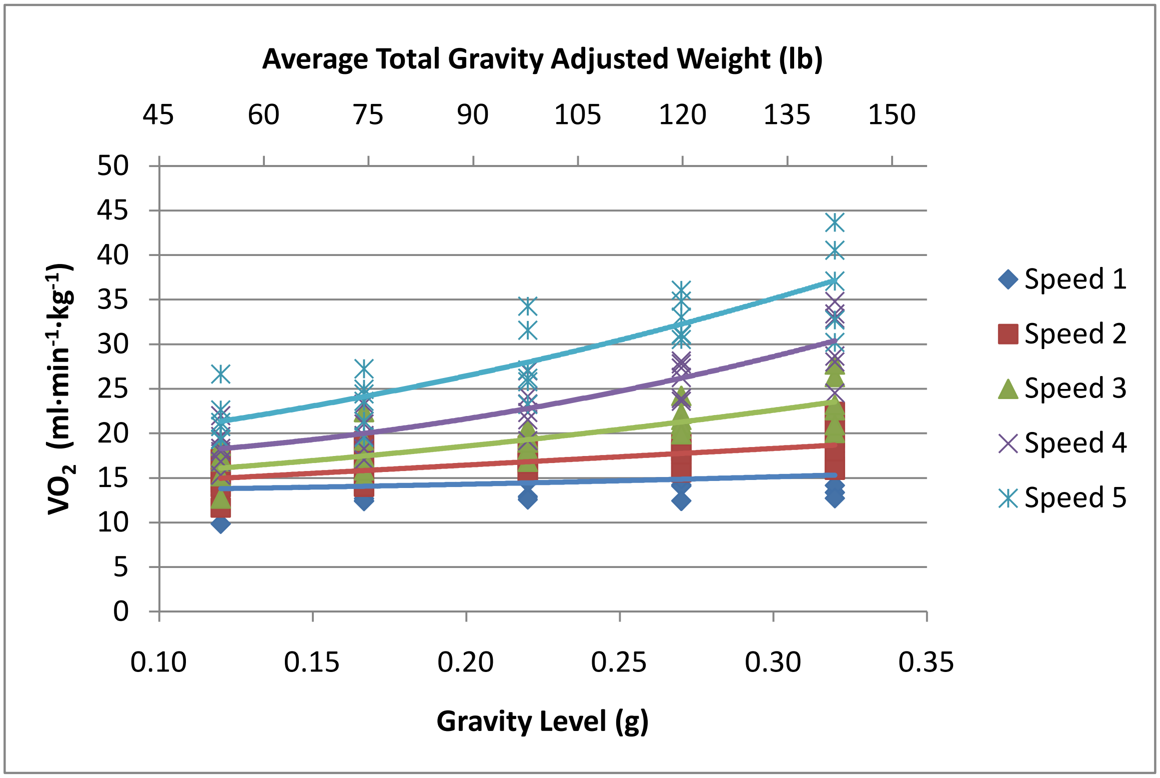

Figure 23. Metabolic rate vs. gravity level or average total gravity adjusted weight during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg).

Figure 24 shows the same relationships with weight-matched unsuited subjects. Although weight alone accounts for an increase in metabolic rate, it made up a smaller portion than expected. At the first four speeds, there is little change in metabolic rate for the unsuited weight-matched subjects although their TGAW almost doubles from 74 to 143 lb.

Subtracting the metabolic rates of the unsuited weight-matched control trials from those of the suited trials resulted in the metabolic cost of the suit not directly related to the increased weight; this result is comprised of factors such as inertial mass, kinematic constraints of the suit, and stability. Figure 25 plots the difference in metabolic rate between suited and unsuited weight-matched subjects as a function of gravity level or TGAW. This difference was significant for all speeds, with the first two walking speeds showing little to no increase as gravity increased but with the faster walking speeds and running speeds significantly increasing as gravity level increased, indicating that interactions between weight and speed exist that were not fully understood.

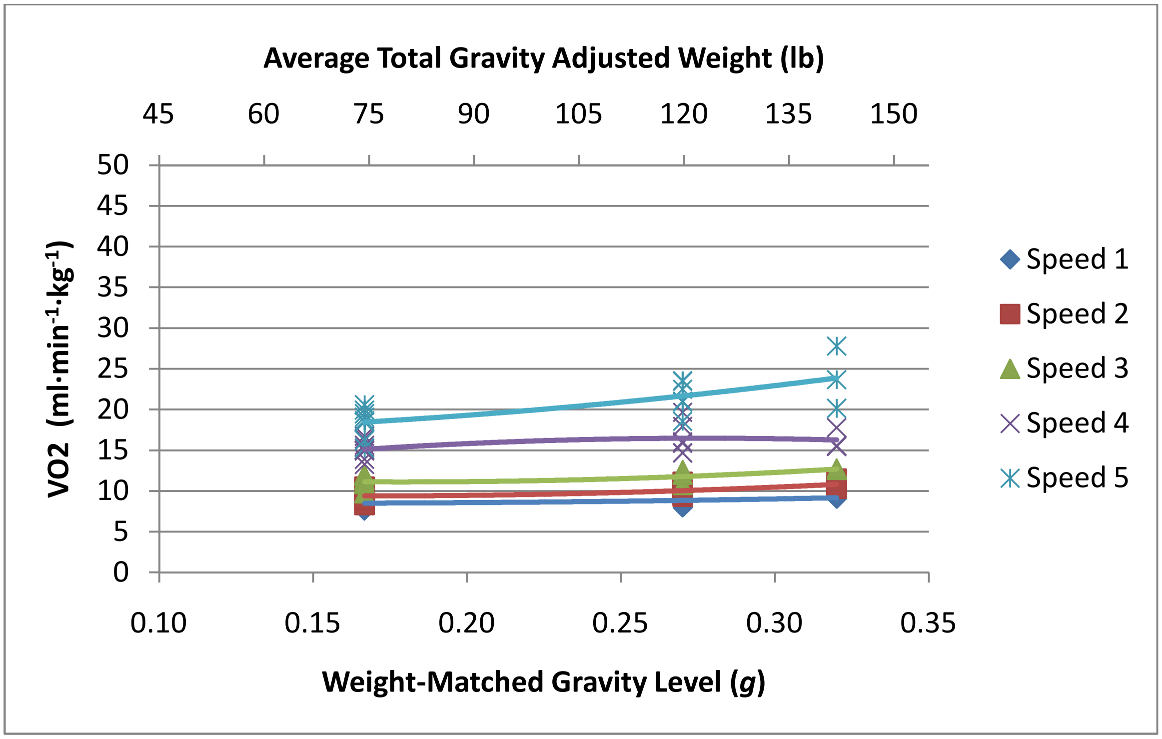

Figure 24. Metabolic rate vs. weight-matched gravity level or average total gravity adjusted weight during unsuited locomotion with constant mass.

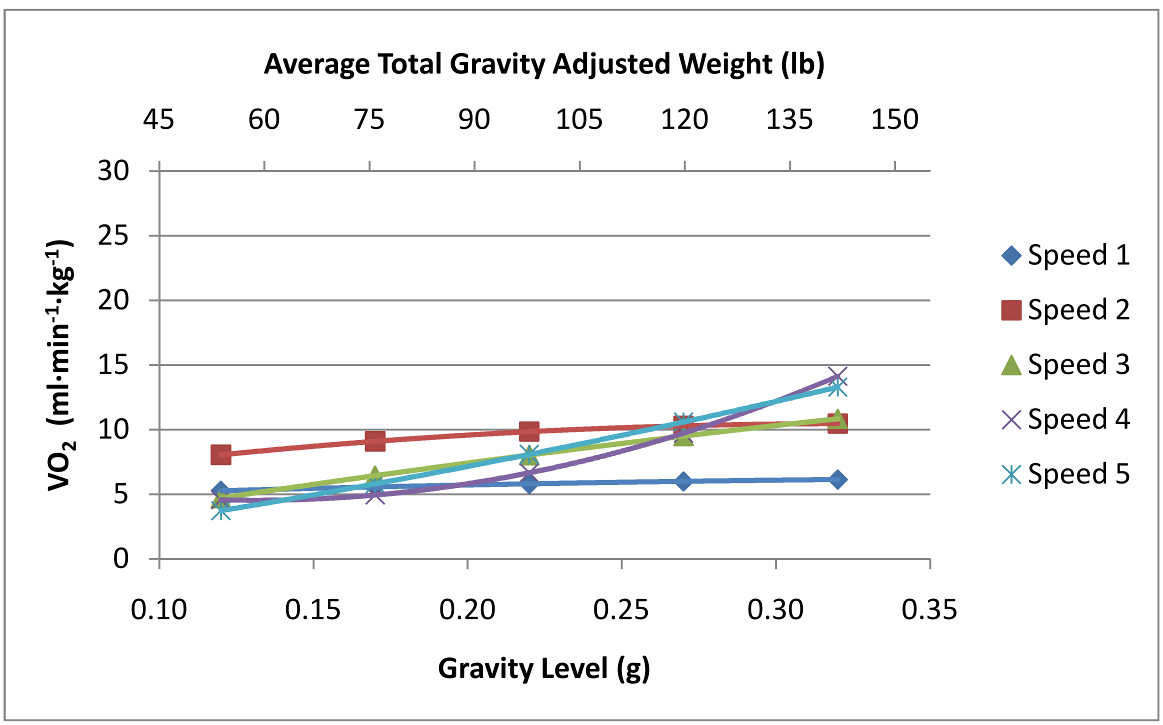

Figure 25. Metabolic cost of the suit not related to weight vs. gravity level at a constant suit pressure of 29.6 kPa and suit mass of 121 kg.

Oxygen Transport Cost

Transport cost is defined as the volume of O_2 required to translate 1 kg of body mass a distance of 1 km. It can be thought of as equivalent to gas mileage. Results are shown in Figure 26. At speeds less than 0.8 m•s^{-1}, the results are mixed and gravity level was not a discriminator of transport costs. The transport cost at gravity levels from 0.12-g to 0.22-g were similar up to speeds of approximately 1.5 m•s^{-1}, the upper end of nominal translation speeds. The two lowest gravity levels showed a continued decrease in transport cost through 2.2 m•s^{-1}. Interpretation of these data in terms of suit mass on the moon would indicate a suit mass of 186 kg or less may be necessary for an efficient 10-km walkback contingency. These data suggest that the most efficient walkback speed range for a 186-kg suit might be 1.4 to 2.1 m•s^{-1}, and the most efficient walkback speed for a 63- to 121-kg suit might be 1.8 to 2.6 m•s^{-1}, although many factors may affect this selection, including cooling limitations (1), terrain (10), and an understanding of how similar a change in TGAW from just an alteration in offload represents a true change in suit mass.

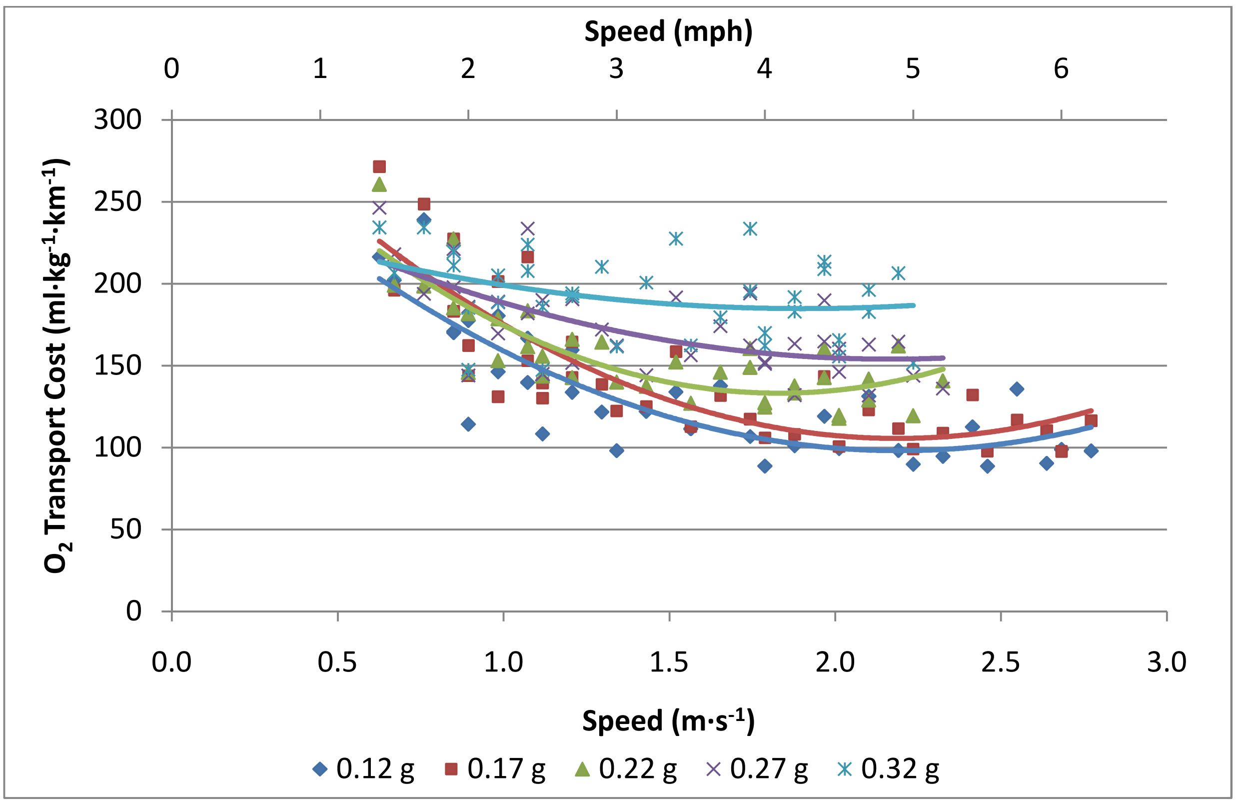

Figure 26. Transport cost vs. speed at different gravity levels during suited locomotion at a constant mass (121 kg) and pressure (29.6 kPa).

Subjective Findings

Subjective findings showed similar trends to the metabolic rate. The general trend. as seen in Figure 27, was that RPE increased as gravity level increased. The difference in RPE between suit weights also increased as speed increased. RPE results were especially similar to metabolic results, which indicate that the subjective RPE data is aligning well with the objective metabolic data and that, in certain reduced gravity analogs where metabolic rate cannot be easily collected, the use of RPE may provide a good indication of performance differences. Figure 28 shows that GCPS ratings were very similar for gravity levels ≤0.22-g at all speeds and were similar at all gravity levels for the two lowest speeds. For the three highest speeds at the two highest gravity levels, GCPS was higher by one to three levels. All subjects at all speeds at gravity levels of ≤0.22-g had GCPS ratings ≤5, with most in the ideal range of ≤3. In many cases, the heavier weights were also acceptable; but several ratings were ≥6, especially at higher speeds.

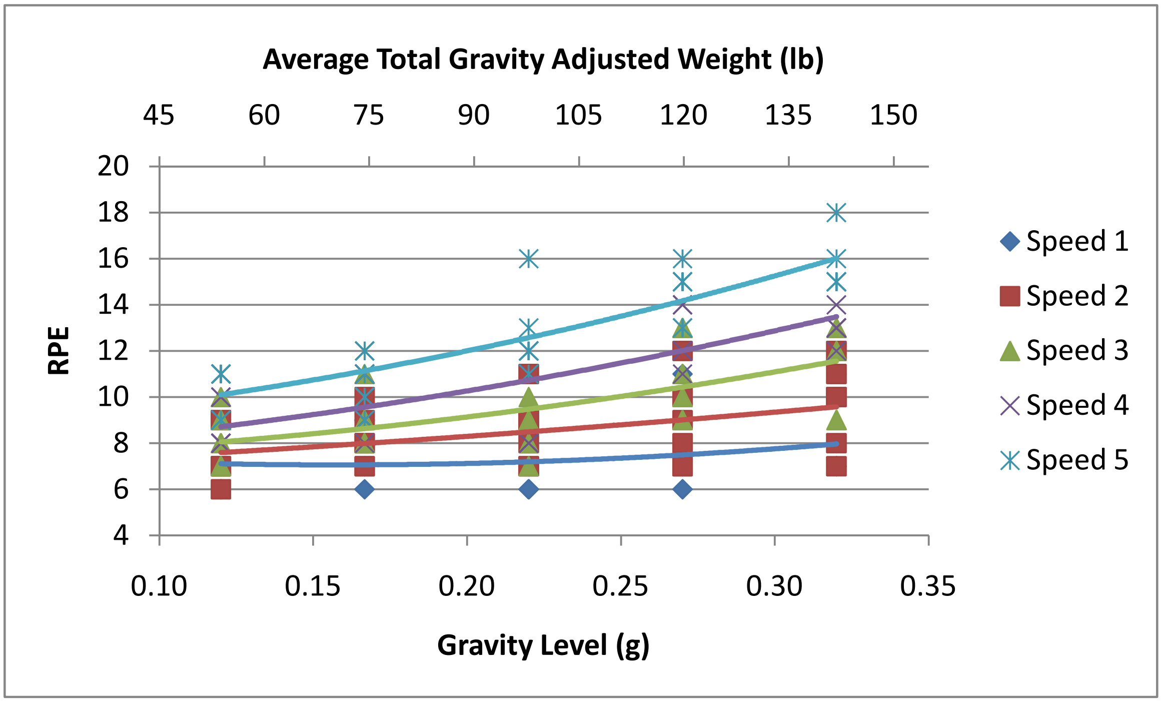

Figure 27. RPE vs. gravity level or average TGAW during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg).

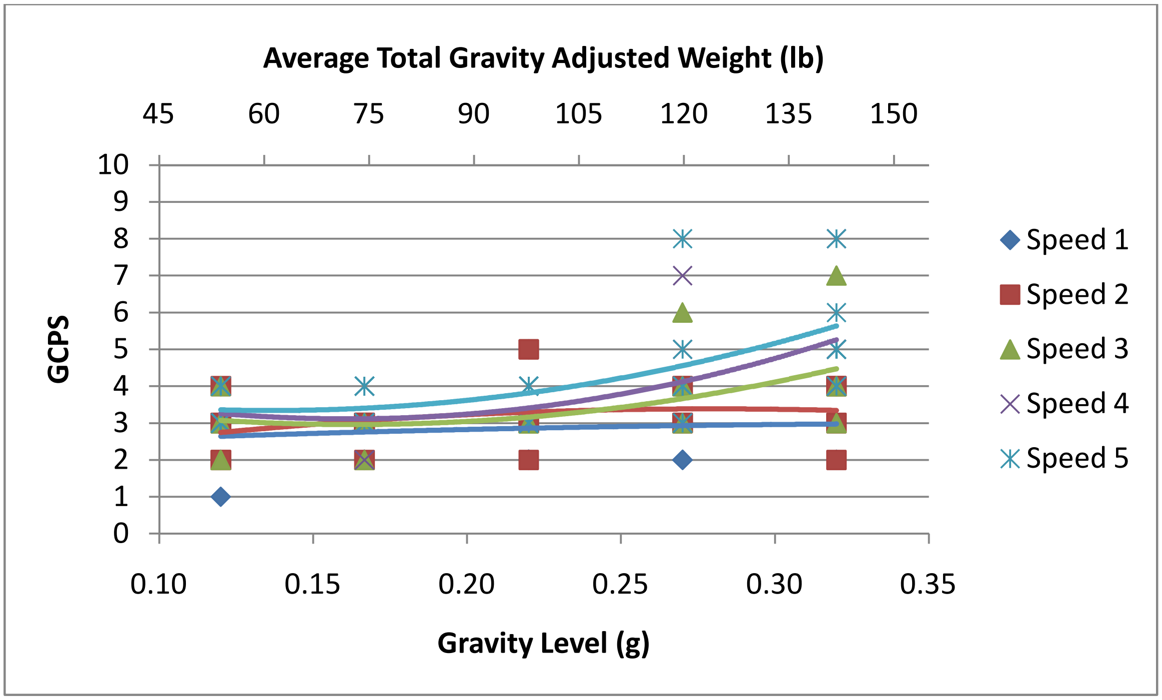

Figure 28. GCPS vs. gravity level or average TGAW during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg).

Biomechanics Findings

GRF is the force a body places on the ground; therefore, it is the resultant force of the ground pushing back on that body. During locomotion, the individual is acted on by the GRF at the time of ground impact. The magnitude of the GRF varies as a function of locomotion speed, increasing with increasing speed. In Earth walking, the vertical component of the GRF has a maximum value of 1 to 1.2 "times body weight" (BW); and in Earth running, the maximum or peak can be as high as 3 to 5 BW (11) (12).

The mean vertical peak GRF vs. gravity level is shown in Figure 29. Unlike the experience of varying the suit pressure, there appears to be a general trend of increasing vertical peak GRF with increasing gravity. This trend was expected because of the increase in weight as gravity increased. There is also a clear trend that GRF increased as speed increased, also as expected. For expected nominal lunar ambulation speeds (speeds 1 to 3), the average GRF did not exceed 1.5 BW even at the heaviest conditions. Only with the increased weight seen at the higher gravity levels and faster running speeds did the GRF approach BW values seen during 1-g running. Although these data are encouraging from a bone and muscle preservation perspective because achieving 1-g type loading may be possible during EVA, it is unlikely that EVA crew members will run significant quantities at higher speeds or that the suit will actually be massive enough to achieve the same TGAW in lunar gravity that was seen at the higher gravity levels tested. Overall, this indicates additional exercise counter-measures may be necessary and EVA alone may not be enough.

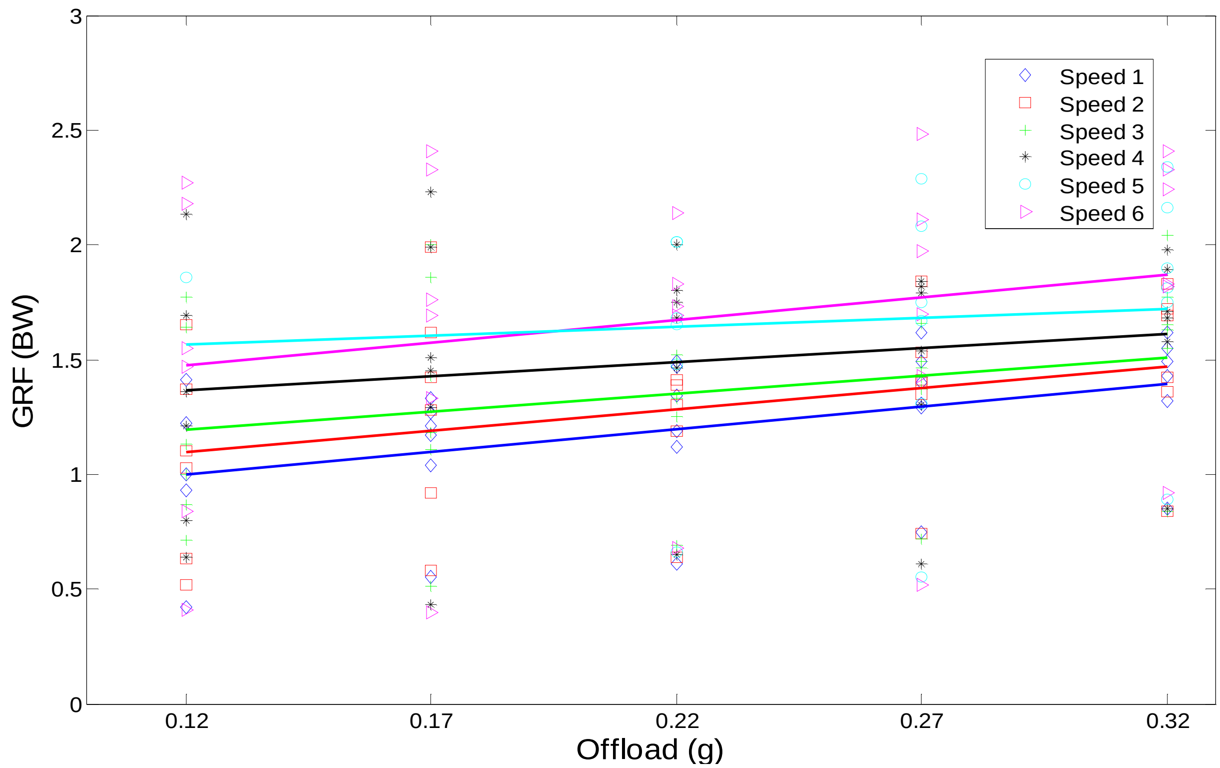

Figure 29. Peak GRF vs. gravity level during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg).

Figure 30 and Figure 31 show that as gravity increased, percentage stance time and cadence, respectively, increased for all locomotion speeds. Together, these data indicate that as gravity increased, subjects spent more time in contact with the ground and used shorter, more frequent strides to compensate for the increased weight.

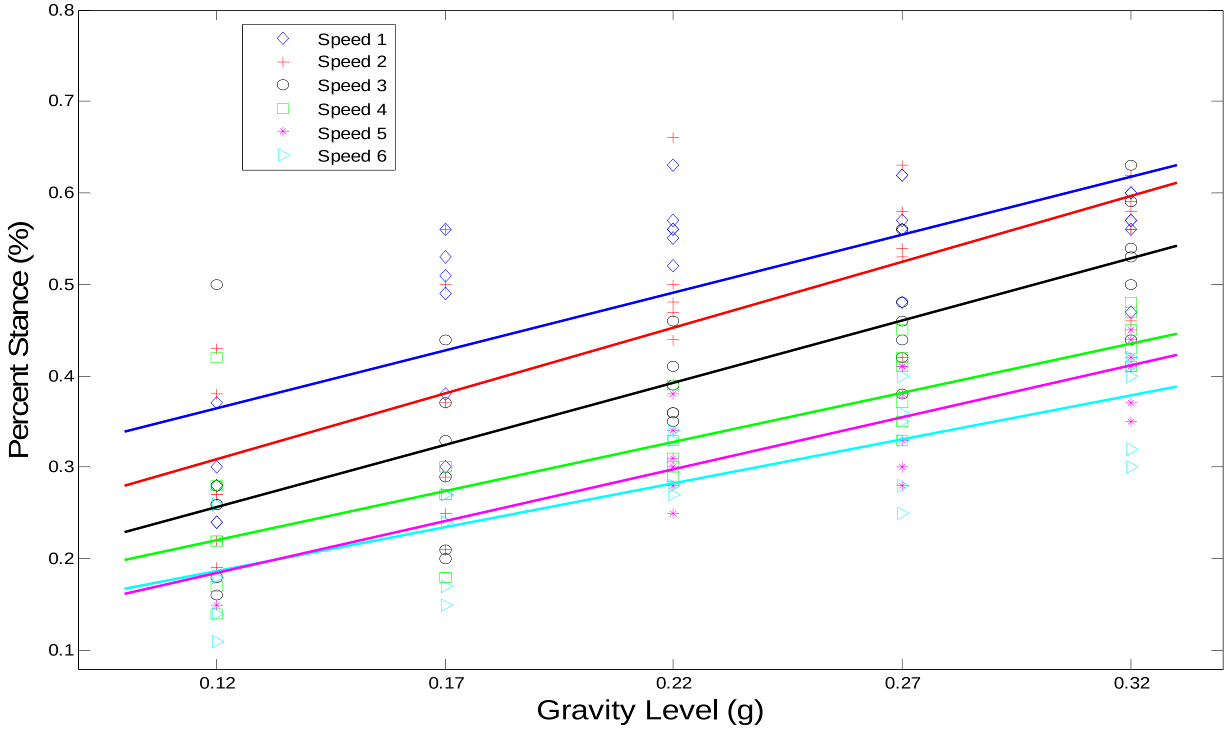

Figure 30. Stance time vs. gravity level during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg).

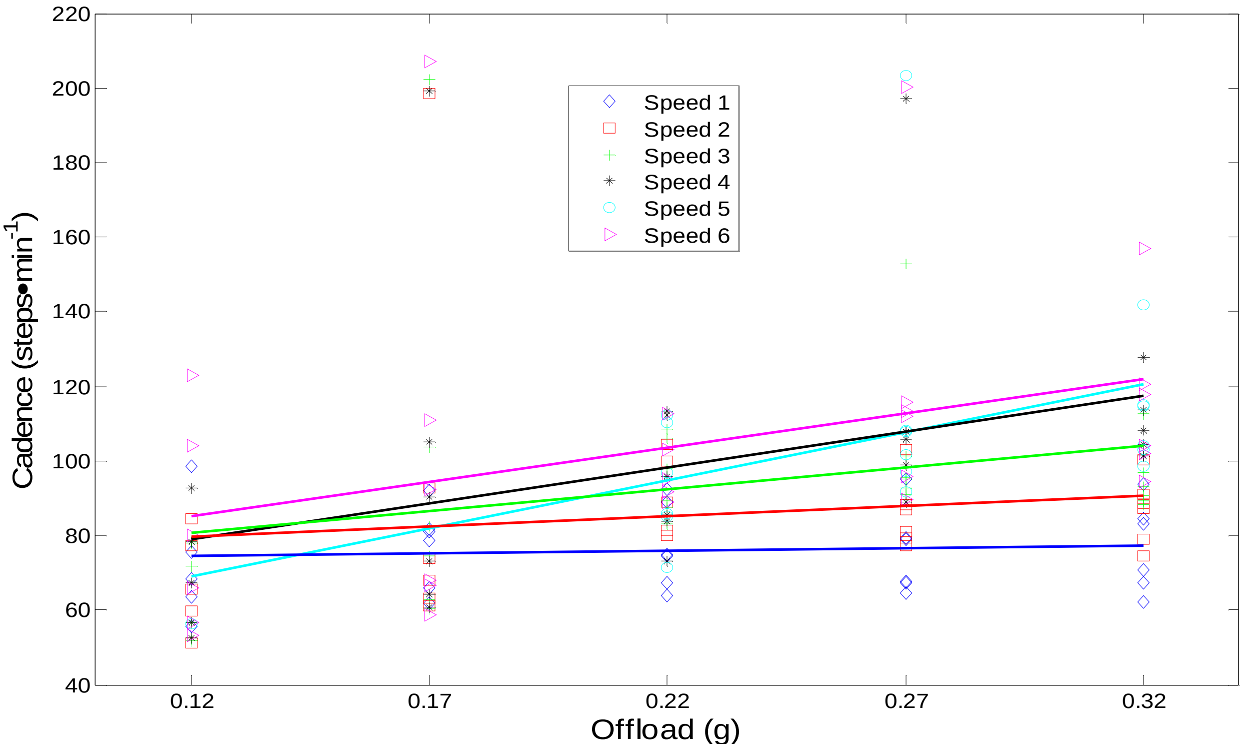

Figure 31. Cadence vs. gravity level during suited locomotion with a constant suit pressure (29.6 kPa) and suit mass (121 kg).

The mean hip, knee, and ankle ROM exhibited an abnormality at 0.22-g similar to the ROM data for varying pressure (Figure 32-Figure 34). The hip and ankle ROM data at 0.22-g appear to have a "trough" across all speeds. The knee ROM at 0.22-g shows a trough across the first two speeds but then demonstrates a ridge for the remaining speeds. This suggests gait kinematics are being altered at this offload. The deviation may be because of the same factors discussed in the varying pressure section, and further study would be needed to understand this phenomenon.

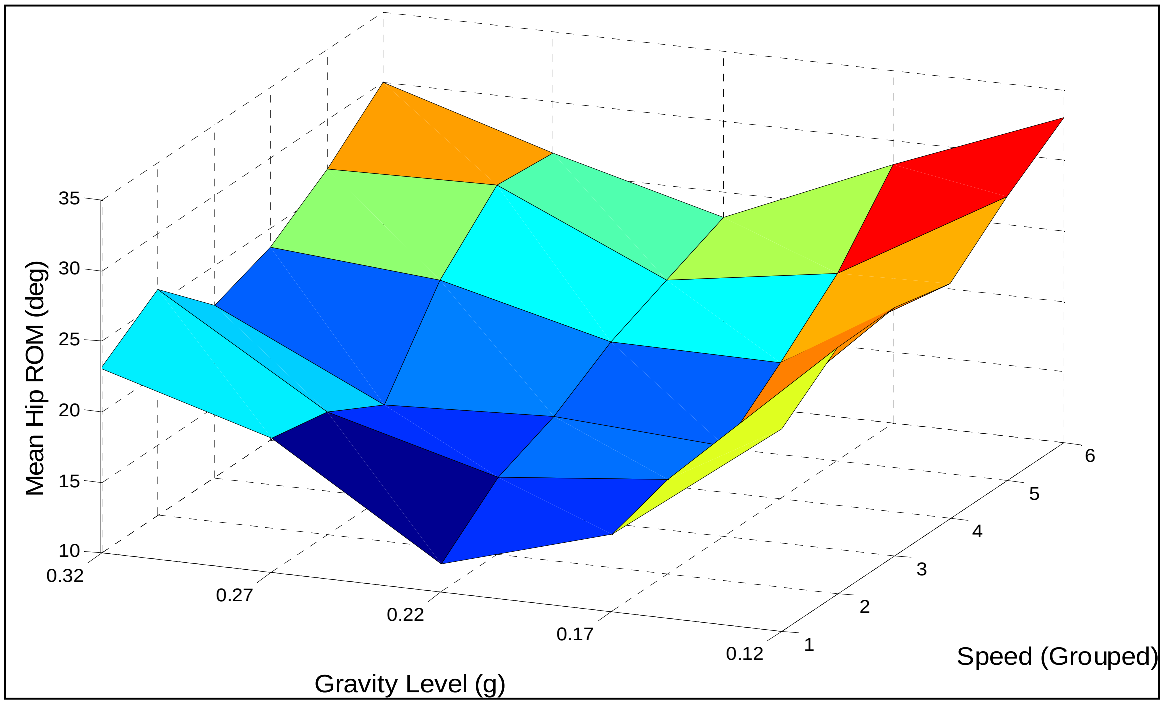

Figure 32. Mean hip ROM during suited ambulation at different gravity levels and speeds. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (greens and blues) demonstrate the lower values observed.

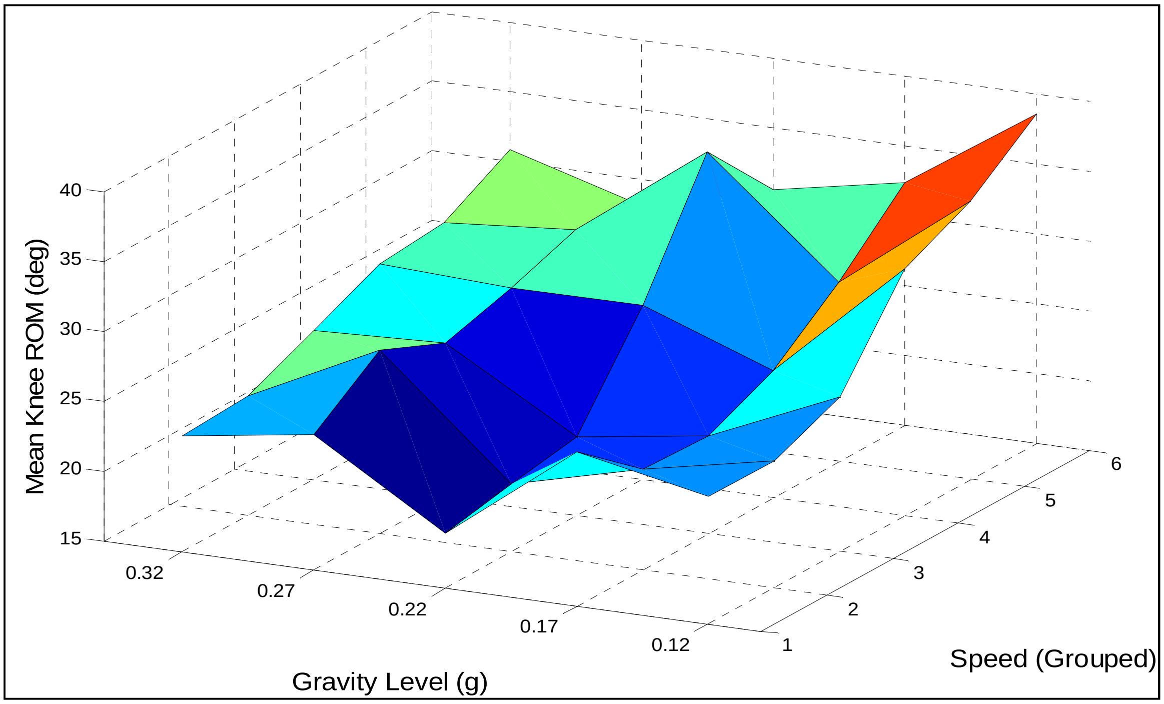

Figure 33. Mean knee ROM during suited ambulation at different gravity levels and speeds. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (oranges and reds) are the extreme values observed. Conversely, the cooler colors (greens and blues) demonstrate the lower values observed.

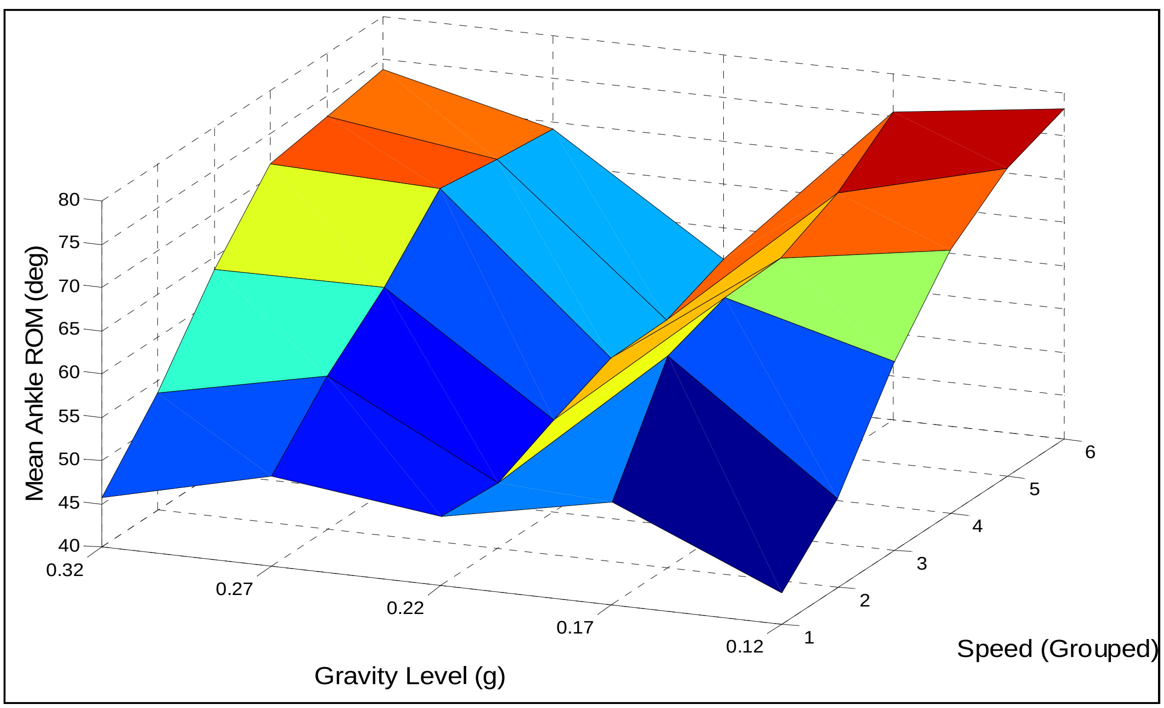

Figure 34. Mean ankle ROM during suited ambulation at different gravity levels and speeds. The parametric colored surfaces represent the ROM value. The color scheme of warm to cool colors indicates the magnitude of the ROM value. The warmer colors (yellows, oranges, and reds) are the extreme values observed. Conversely, the cooler colors (greens and blues) demonstrate the lower values observed.

As weight increased, stance time, cadence, and peak vertical GRF also generally increased. Joint ROM for the hip, knee, and ankle showed inconsistent trends and an anomalous finding at 0.22g. Coupling these biomechanics changes with the metabolic data indicates that with increasing weight, there is likely an increase in mechanical work being done. This increase could be seen as advantageous as an exercise countermeasure, but disadvantageous for preserving EVA consumables.

Another biomechanical parameter employed to examine the effects of offload was the Floquet multiplier, a tool that is commonly used to transform periodic cycles to a traditional linear system known as Floquet's theory**.** Simply, Floquet's theorem uses ordinary differential equations to convert a periodic function into a traditional linear function. End results of Floquet's theorem are eigenvalues, ranging between 0 and 1, of the mathematical matrix that defines the linear system. In gait studies, eigenvalue is often used as a measure of stability (13). Since many gait cycles occur during walking, the maximum eigenvalue is identified. This maximum eigenvalue is used as an overall stability measure because it is the value that dominates the dynamic system. In other words, the closer the maximum eigenvalue is to the value of 1, the less stable the person is walking and the longer it takes that individual to return to steady-state locomotion. If the maximum eigenvalue exceeds the value of 1, the person has become so unstable that he/she has fallen or tripped. For purposes of gait analysis in this report, we use the term "Floquet multiplier" as a more specific name for the eigenvalue derived from Floquet's analysis. The Floquet multiplier data did not demonstrate any observable trends across speeds or offload (Figure 35).

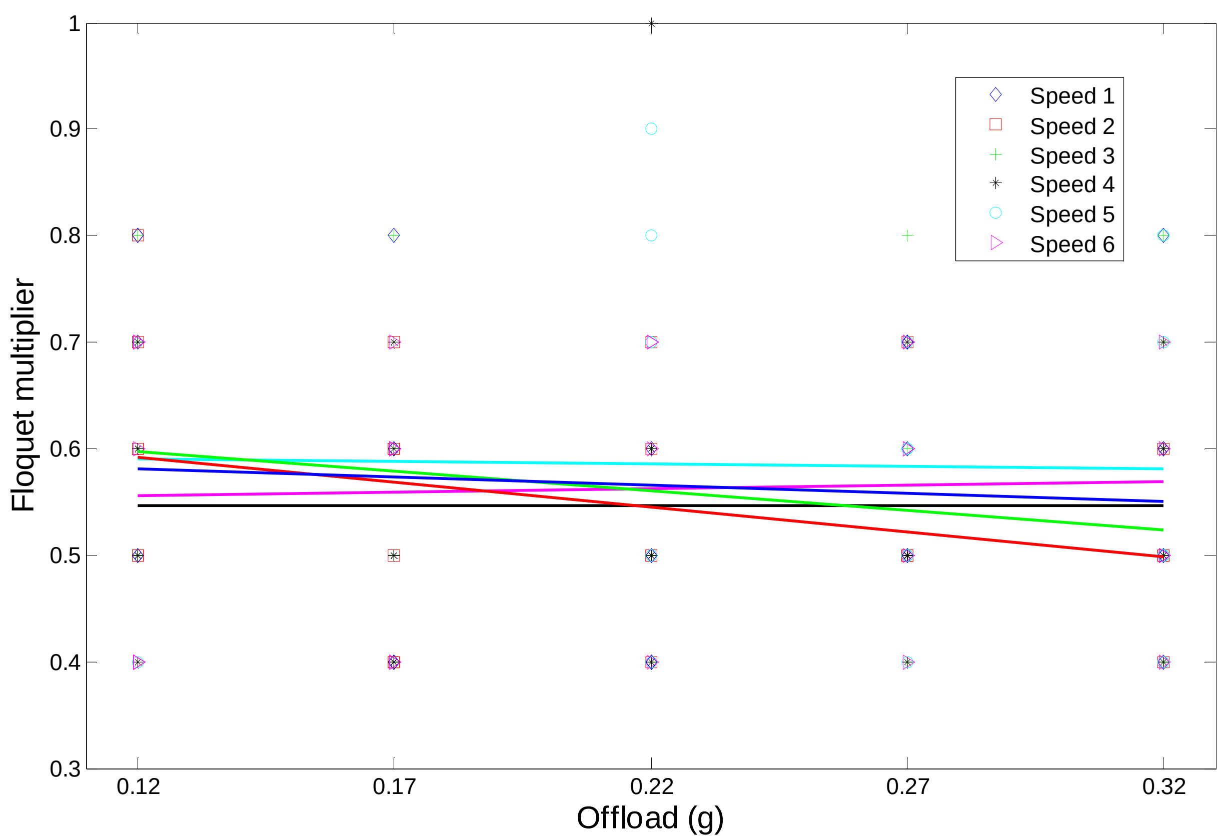

Figure 35. Floquet multiplier during suited ambulation at different gravity levels and speeds.

3.2.3 Effect of Varied Mass

Initial findings showed no significant differences in metabolic rate as a function of added inertial mass to constant weight subjects (Figure 36).

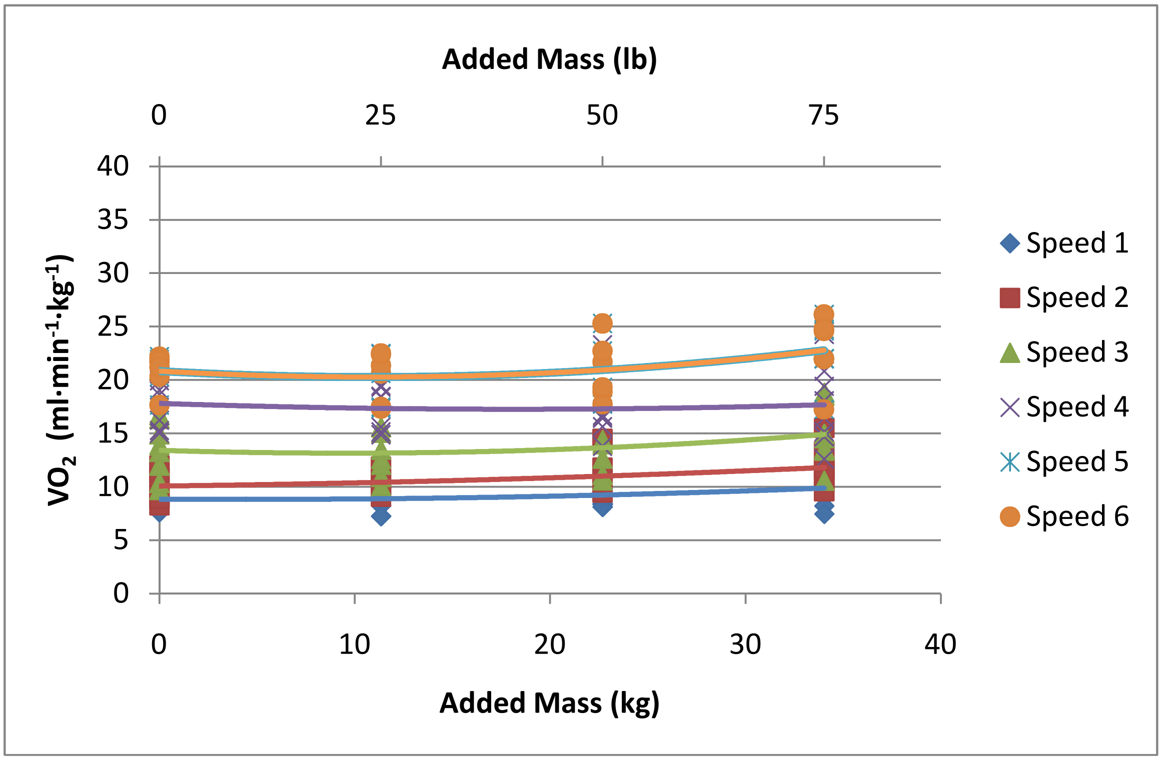

Figure 36. Metabolic rate vs. added mass increments for unsuited locomotion while weight-matched to the 121-kg suit mass/weight at lunar gravity.

One possible reason for this lack of variation is the limited ROM due to the alteration in the tension of the straps providing overhead suspension on subjects wearing the weight vest. Another reason may be that the mass was not evenly distributed across the whole body, but was limited to the torso. Finally, the increments tested may have been too small to see a realistic trend. The initial plan to use the unpressurized MKIII suit without a helmet to establish a 121-kg mass was not practical as increased joint wear was observed from ambulating in the unpressurized suit (see Appendix D for further details). Modifications to the gimbal support system to accommodate both unsuited and suited subjects along with the ability to add and remove mass to the system would provide a better platform on which to investigate the effects of inertial mass.

3.3 Test Objective 3: Compare MKIII at POGO Configuration to the MKIII at POGO Configuration with the Waist Bearing Locked

To evaluate whether a waist joint may be necessary for ambulation in a spacesuit, the waist bearing was locked at the POGO configuration of 121 kg, 29.6 kPa (4.3 psi), and 1/6-g. This prevented rotation of the waist, but the convolutes still allowed flexion and extension. The metabolic data indicated that locking the MKIII waist bearing did not affect metabolic rate during level-ground ambulation (Figure 37).

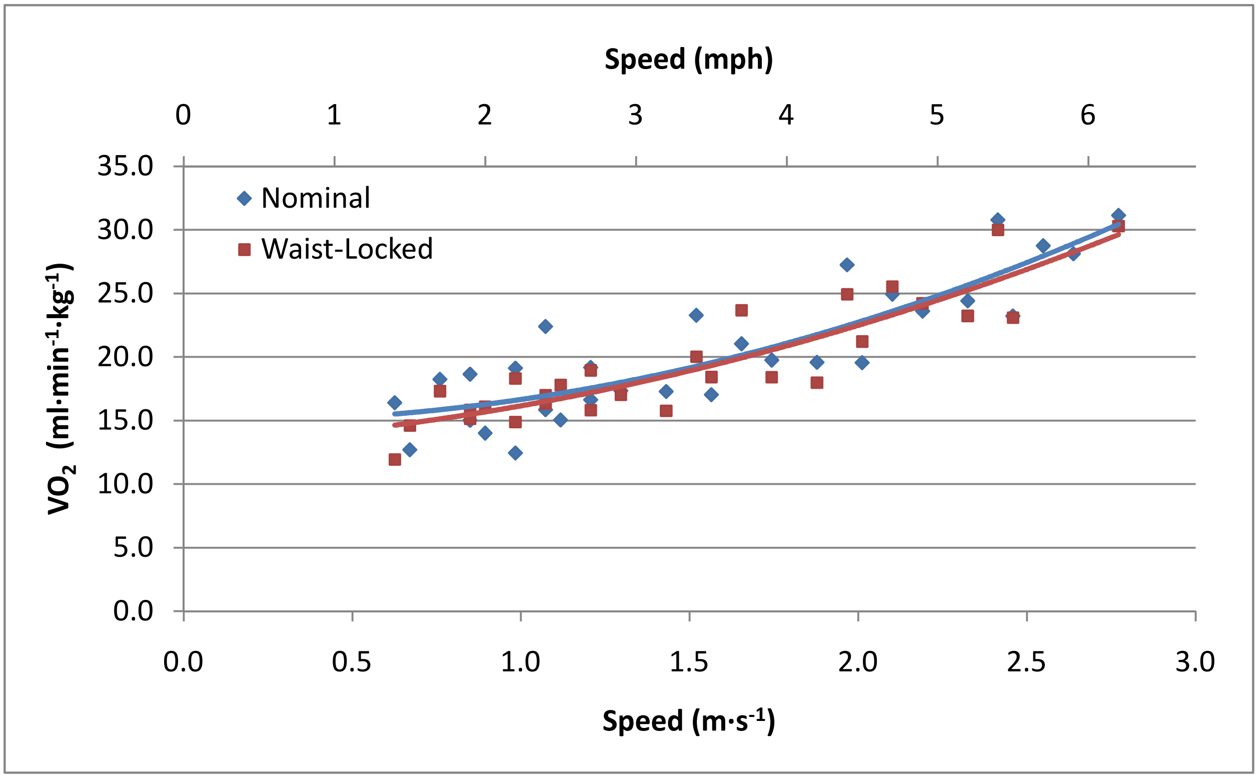

Figure 37. Metabolic rate with the MKIII waist bearing locked compared to nominal suit configuration during suited ambulation at lunar gravity with a suit mass of 121 kg and suit pressure of 29.6 kPa.

While the metabolic rate did not differ between nominal and waist-locked conditions, the subjective ratings did differ. As shown in Figure 38-Figure 39, the average RPE was slightly higher for the waist-locked condition vs. the nominal condition. The waist-locked condition was always performed last, which could explain the increased exertion levels over the nominal conditions. The GCPS values for the waist-locked condition were higher than without the waist locked. However, the average GCPS ratings were below four for the waist-locked condition. Although GCPS ratings were higher in the waist-locked condition, there was no difference in metabolic rate. This indicates that while subjects felt it required more compensation to maintain performance, they were not expending any more energy to compensate.

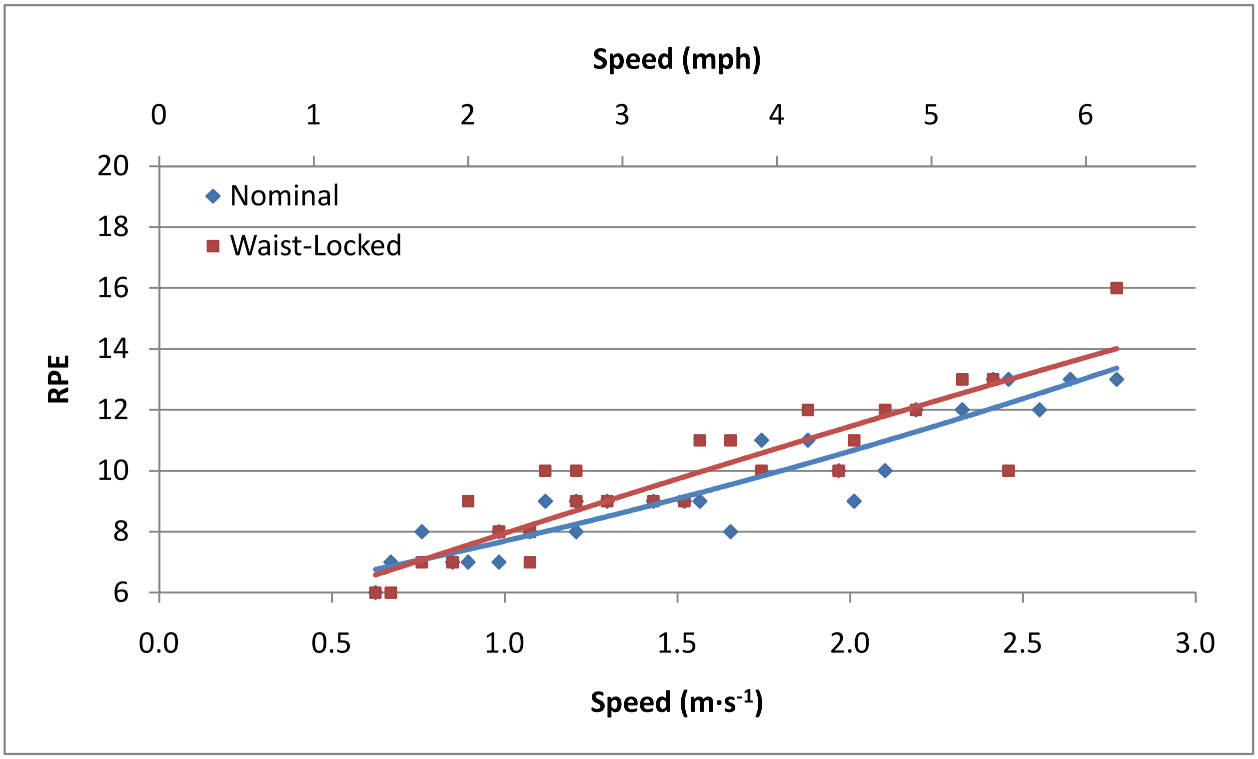

Figure 38. RPE with the MKIII waist bearing locked compared to nominal suit configuration during suited ambulation at lunar gravity with a suit mass of 121 kg and suit pressure of 29.6 kPa.

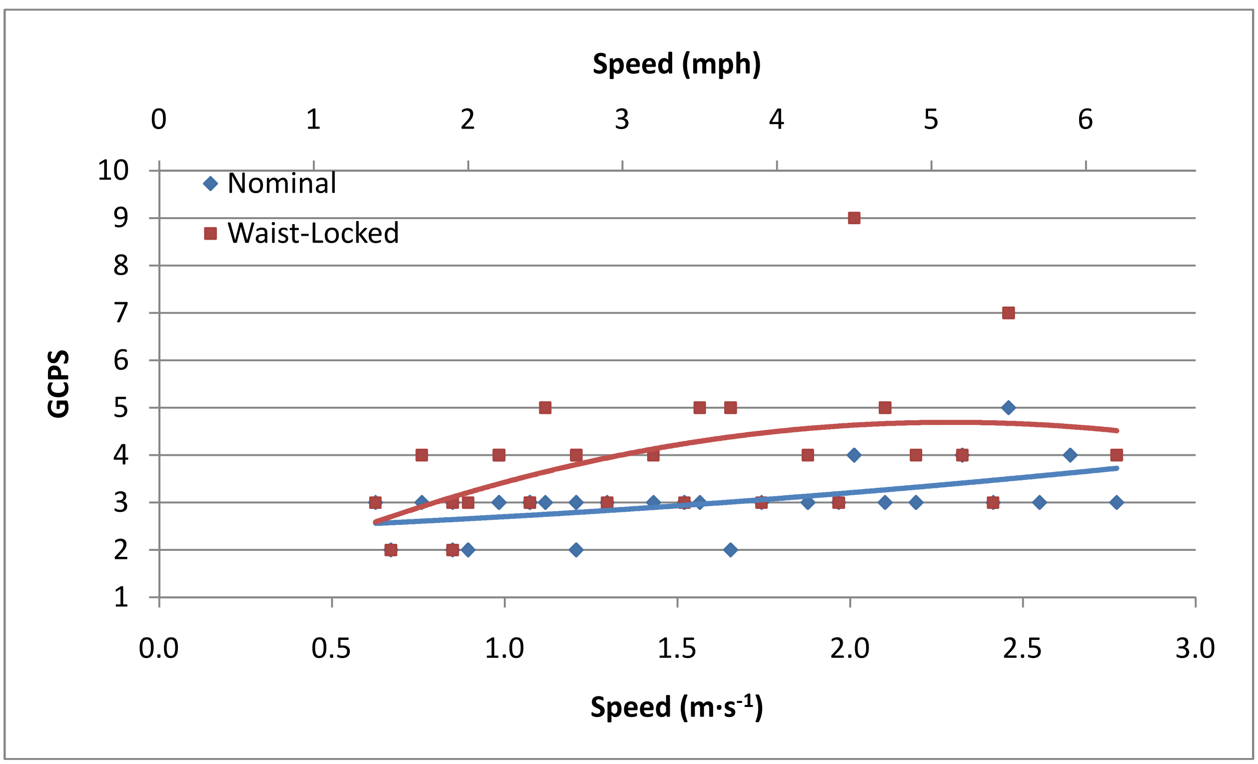

Figure 39. GCPS with the MKIII waist bearing locked compared to nominal suit configuration during suited ambulation at lunar gravity with a suit mass of 121 kg and suit pressure of 29.6 kPa.

The calculated hip and knee ROM percentage change between the waist locked and unlocked conditions are provided in Table 4 and Table 5 for five of the six subjects (one subject did not complete the task). There was no observable difference between the conditions. This comparison was heavily dependent on the type of gait style chosen by the subjects. The type of gait style chosen by each subject is also roughly categorized and provided in Table 4 and Table 5.

Table 4. Hip ROM Percentage Change Between Waist Locked and Unlocked Conditions for Speeds 3 through 6

	Speed 3	Speed 4	Speed 5	Speed 6	Avg.	Locked	Unlocked
Subject B	35	39	36		**37**	Hop	Bound
Subject C	–31	–14	4		**–14**	Hop	Hop
Subject E	–7	48	19	14	**19**	Hop/Bound	Hop/Bound
Subject G	–6	17	12	7	**8**	Hop/Bound	Bound
Subject H	–14	–4	–6	–17	**–10**	Run	Skip
Average	**–5**	**17**	**13**	**2**			

Table 5. Knee ROM Percentage Change Between Waist Locked and Unlocked Conditions for Speeds 3 through 6

	Speed 3	Speed 4	Speed 5	Speed 6	Avg.	Locked	Unlocked
Subject B	–9	25	–5		**4**	Hop	Bound
Subject C	25	6	1		**11**	Hop	Hop
Subject E	32	19	10	0	**15**	Hop/Bound	Hop/Bound
Subject G	16	29	26	34	**26**	Hop/Bound	Bound
Subject H	16	17	13	1	**12**	Run	Skip
Average	**16**	**20**	**8**	**17**			

3.4 Test Objective 4: Predictive Models of Metabolic Rates, Subjective Assessments, and Suit Kinematics

Test Objective 4 was "to develop predictive models of metabolic rates, subjective assessments, and suit kinematics based on measurable suit, task, and subject parameters." Development of these models will eventually provide the NASA community with an easy-to use-tool that highlights the performance changes associated with manipulation of the suit, subject, and EVA characteristics. These models also could be used to prospectively predict results for future tests to validate or further refine the model against those results. It is our goal that the results of this test series can become a validated model accessible to all within the EVA science, engineering, and operations community.

3.4.1 Predictive Model for Metabolic Rate No. 1

A preliminary multiple linear regression model was developed to predict the metabolic rate of locomotion in the MKIII suit as a function of the properties of the suit, anthropometry of the subject, and speed of locomotion. The model was developed as an example of the type of predictive model that will be developed and refined in greater detail as additional integrated suit test data are collected and analyzed. Inferential statistics were not calculated because of the small sample size (n=6).

The input variables were the subject weight and leg length, total gravity adjusted weight, suit pressure, and ambulation speed. The preliminary model used the following combination of variables to predict normalized metabolic rates during locomotion in the MKIII EVA suit:

Equation 1. Model for predicting metabolic rate based on suit, task, and subject parameters

$$MR = b_0 + b_1 \cdot (V_{locomotion} \times W_{total}) + b_2 \cdot M_{body} + b_3 \cdot (W_{total} \times L_{leg}) + b_4 \cdot P_{suit}$$

where:

MR	= metabolic rate expressed as normalized VO_2 ($mL \bullet kg^{-1} \bullet min^{-1}$)
$V_{locomotion}$	= locomotion speed ($m \bullet s^{-1}$)
W_{total}	= total gravity adjusted weight of EVA suit plus astronaut (N)
M_{body}	= body mass of unsuited astronaut (kg)
L_{leg}	= leg length of astronaut (cm)
P_{suit}	= suit pressure (kPa)

The method of least squares was used to estimate the parameters ($b_0 - b_4$) from the experiment data. Predictor variables used in the model were chosen (a) to produce as good a fit as possible with a minimum number of terms and (b) to contain reasonable explanatory information. The proportion of variance explained by the preliminary model (R^2) was 0.846 and the root mean square error was 2.52 $mL \bullet kg^{-1} \bullet min^{-1}$, which was less than the previously determined value of significance, 3.5 $mL \bullet kg^{-1} \bullet min^{-1}$.

Cross-validation was performed by estimating model parameters from experimental data from half the subjects (subset 1) and using those parameters to predict the experimental observations recorded for the remaining subjects (subset 2). This process was repeated by estimating model parameters using subset 2 data and those parameters to predict subset 1 observations. Thus, the model parameters were estimated using three different data sets: using all data, using subset 1 data, and using subset 2 data. In all three cases, the signs of the model parameters were consistent, the proportion of explained variance correlation coefficient (R^2) was 0.831 or greater, and the root mean square error did not exceed 2.61 $mL \bullet kg^{-1} \bullet min^{-1}$ when each subset model predicted metabolic rates for the other half of the data.

The large proportion of explained variance (R^2) and the small root mean square error combined with the results of the cross-validation analysis indicate that this preliminary model provides good prediction of normalized metabolic rates for this data set. However, this model should not be generalized beyond the conditions under which the data were collected. Descriptive statistics for the six astronaut subjects are shown in Table 1. The range of experimental conditions is shown in Table 6.

Further data collection planned in forthcoming suit test protocols combined with detailed characterization of subject anthropometry, strength, and fitness will enable development of the model such that it may be generalized to a larger range of EVA tasks, suit configurations, and astronaut populations.

Table 6. Range of Experimental Conditions On which the Preliminary Model Is Based

		P_{suit}				
Gravity Level	**Total Gravity Adjusted Weight**	**6.9 kPa (1.0 psi)**	**20.7 kPa (3.0 psi)**	**29.6 kPa (4.3 psi)**	**34.5 kPa (5.0 psi)**	**44.8 kPa (6.5 psi)**
0.12g	222–245 N (50–55 lb)			0.64–2.78 $m \cdot s^{-1}$		
0.17g	307–343 N (69–77 lb)	0.64–2.78 $m \cdot s^{-1}$	0.64–2.78 $m \cdot s^{-1}$	0.64–2.78 $m \cdot s^{-1}$	0.64–2.78 $m \cdot s^{-1}$	0.64–2.78 $m \cdot s^{-1}$
0.22g	405–449 N (91–101 lb)			0.64–2.78 $m \cdot s^{-1}$		
0.27g	498–552 N (112–124 lb)			0.64–2.33 $m \cdot s^{-1}$		
0.32g	592–654 N (133–147 lb)			0.64–2.33 $m \cdot s^{-1}$		

The application of this model is currently limited to level-ground ambulation with the subjects and conditions described in Table 1 and Table 6. Currently, this model is a statistically descriptive fit for the IST-1 data, but we plan to develop a more generalized predictive model for metabolic cost, whose parameters can be optimized from a range of suit test data Further expansion of this model will include incline walking and various exploration tasks as these activities have different subject-suit interactions.

Given the limitations of this current model, it is still important to demonstrate the utility of a predictive model of metabolic rate as it relates to determining suit and EVA consumable requirements.

We have previously described 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ as the level of significance for metabolic rate. Using the model to predict metabolic rate, this cut-off point for practical significance is greater than the root mean square error of 2.52 $mL \cdot kg^{-1} \cdot min^{-1}$. Figure 40 demonstrates the predictive accuracy of this descriptive model by showing the majority of predictions are clustered tightly around measured VO_2. Further review indicates the majority of predicted values are within 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ of measured VO_2 independent of speed.

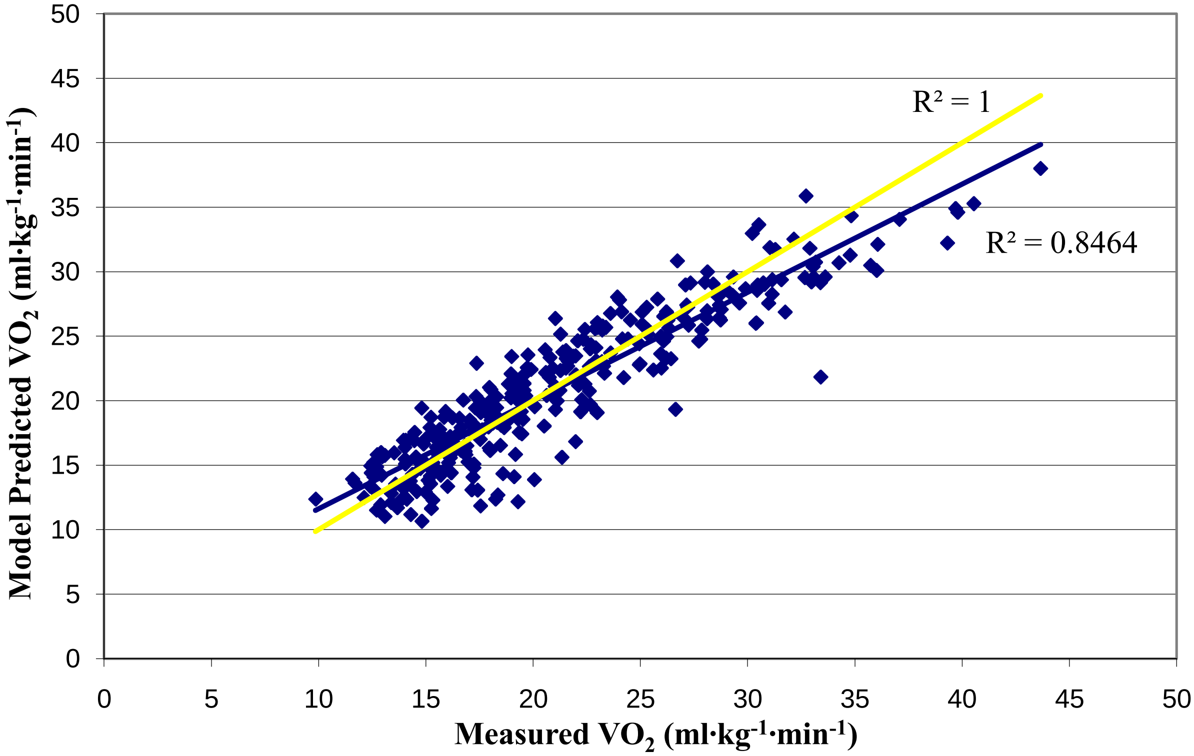

Figure 40. Difference between model predicted and measured VO_2 vs. speed for all suited data collection points.

Preliminary application of this model would encompass locomotion only. Recommendations for suit pressure would assume a 121-kg suit/system mass, and recommendations for suit mass will assume a 29.6-kPa (4.3 psi) suit pressure currently relying on the assumption that a change in weight (TGAW) reasonably represents a change in suit mass. Application of the model requires a set of assumptions for the speeds expected during locomotion. Digital video analysis from the Apollo films, as well as inputs from the Lunar Architecture Team and results of the EWT, provides the following set of assumptions regarding operational concepts for lunar exploration:

- 0.4 to 0.8 m•s^{-1} (~1.0 to 2.0 mph) is the range assumed for intrasite translations for various contextual observations and EVA tasks.
- 1.1 to 1.4 m•s^{-1} (~2.5 to 3.0 mph) is the range of ambulation speeds for site-to-site translations defined as direction translation between points of interest (this speed range may be less important if crew members use a rover for the majority of site-to-site translations).
- 1.8 m•s^{-1} (~4 mph) is assumed as the optimal speed for a 10-km walkback contingency (1). With an operational concept employing dual rovers, the walkback contingency would not be required in response to a failed rover; however, high-speed translations might be required for short distances to return to life support on the rover in response to various suit malfunctions.

This predictive model of metabolic rate can be used as a tool to understand how suit weight and/or pressure affects the overall metabolic cost and, thus, consumables usage under different operational concepts. The predictive model suggests that suit pressure from 6.9 to 44.8 kPa at a suit mass of 121 kg did not significantly change metabolic rate across the range of ambulation speeds from intrasite translations to contingency walkback. The predictive model for EVA shows significant differences in metabolic rate depending on suit weight and ambulation speeds. Figure 41 demonstrates how varying the mass of the suit up or down from the baseline 121-kg configuration at 29.6 kPa (4.3 psi) changes the metabolic rate as a function of speed within various operational ranges for level-ground ambulation. At this time, the model is limited to level-ground ambulation in the MKIII suit and relies on the assumption that a change in weight, as was tested during IST-1, reasonably represents a change in suit mass. Future studies should determine whether a change in weight reasonably represents the true change in metabolic rate that would be seen with that same change in suit mass. In the future, models will expand to include ambulation as a function of inclination angle and performance of various exploration tasks.

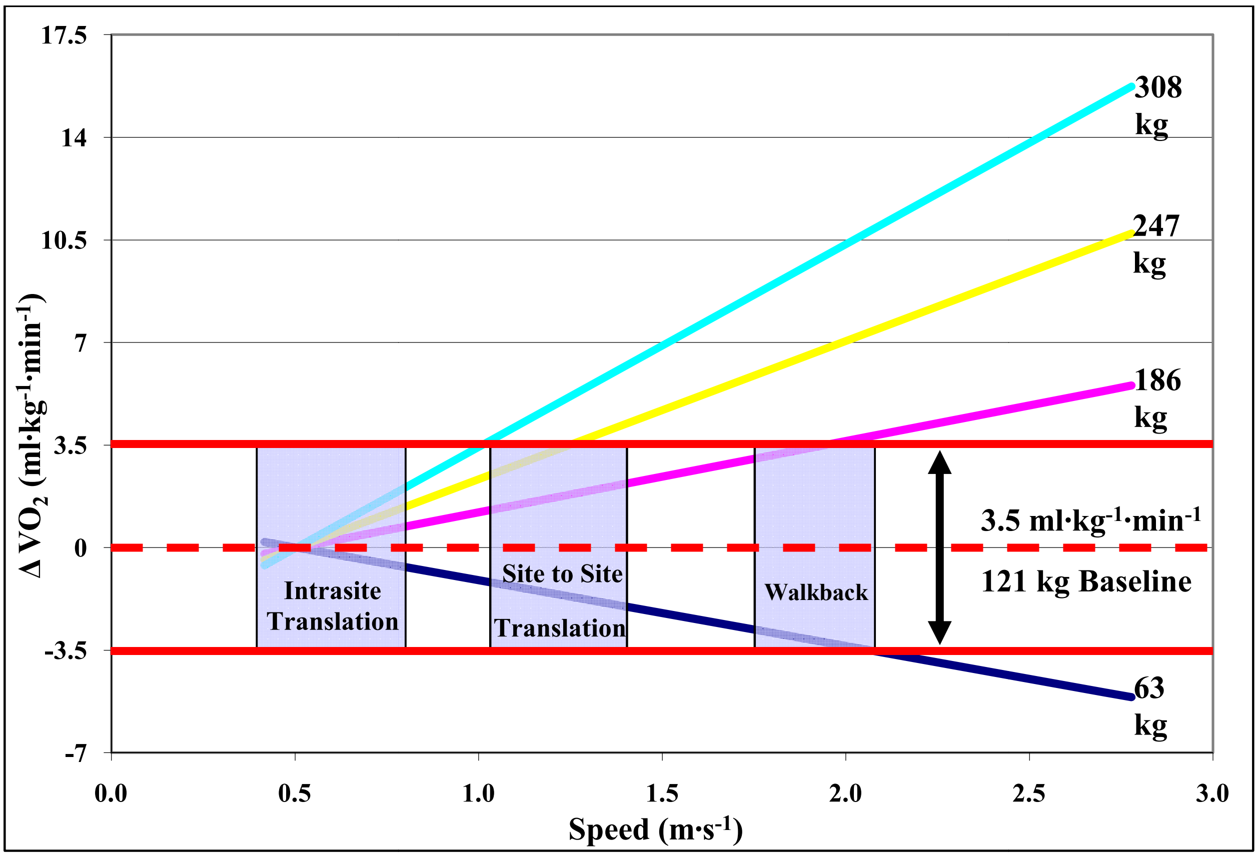

Figure 41. Modeled data showing theoretical ΔVO_2 at 29.6 kPa as suit mass varies from 121 kg across different operational speeds.

Figure 41 suggests that for intrasite translations, no significant metabolic difference between any of the suit masses would occur. For site-to site-translations, suit masses between 63 to 186 kg would not differ significantly; the 308-kg suit would be significantly higher than the baseline configuration for the full range of site-to-site translations speeds, while the 247-kg suit would be significantly higher for the upper range of speeds. For the walkback contingency, significant differences would occur between the baseline configuration and all other suit masses with the 63 and 186 kg suits just beginning to be significantly different in the positive and negative directions, respectively. Preliminary and unverified application of this model might indicate that although weight significantly affects metabolic cost, a larger-than-expected range of suit masses from 63 to 186 kg might be acceptable for the various operational translation speed ranges.

3.4.2 Predictive Model for Metabolic Rate No. 2

For this study, we focus on predicting VO_2 from subject's GCPS and RPE, and on whether the subject was suited for the task (Suit). Mixed-effect regression analysis was used to model VO_2 from RPE, Suit, and GCPS scores, including subject-level grouping to accommodate for the dependence in the data (i.e., repeated observations within subjects), and a random intercept term to allow subjects to vary randomly on the y-intercept of the model. Log transformations of the VO_2 outcome before predictive modeling was done to improve the non-normal distribution of the data and the residuals from our statistical model. The model residuals appeared normally distributed with constant variance over the range of the outcome, suggesting the transformed data are appropriately analyzed with these techniques.

The model revealed that two of three predictors made significant variance contributions to VO_2 in this multivariate context ($P<.05$), with the highest relative contribution observed for the RPE predictor. In this data set, GCPS was not a statistically significant component of the model, but it was included because it increased the overall predictive accuracy of the model and had been a significant component in a similar model constructed with the EWT dataset. RPE scores were positively correlated with VO_2, suited VO_2 was higher than unsuited VO_2, but GCPS scores were negatively associated with VO_2 in this model. Model predicted and observed VO_2 values are shown in Figure 42. Variation in VO_2 seen per unit of RPE is not fully characterized by the model but, rather, model-predicted values cluster around the mean.

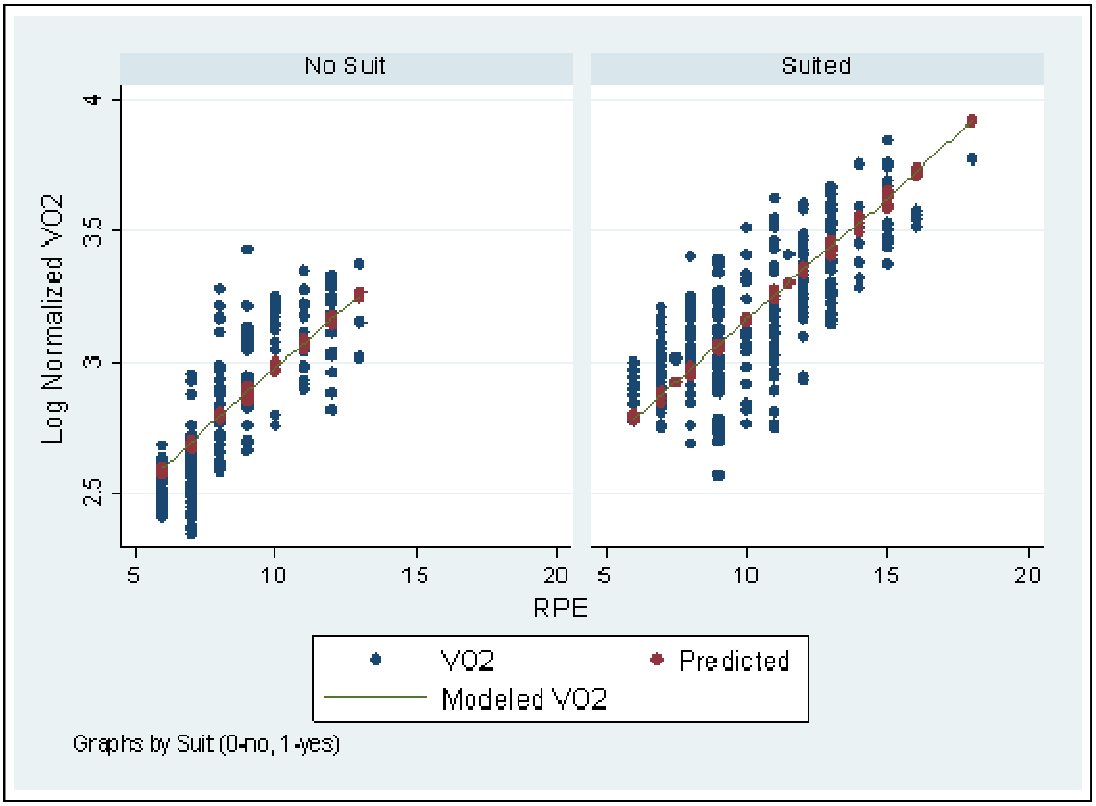

Figure 42. Model-predicted VO_2 (red) and observed VO_2 (blue) with respect to RPE.

While these effects are statistically significant to traditionally held scientific standards, the reader is reminded that they are based on a very small sample of n=6 astronauts. We remain cautious about making inferences to the larger astronaut population or outside of level-ground ambulation until these results can be replicated in future work.

3.4.3 Predictive Model for Subjective Ratings

A predictive model for RPE was created using the same methods as described for the metabolic rate model,. Using ordered logistical regression, a model to predict the probability of a certain GCPS range was also created. As described previously, these are preliminary descriptive models that currently only apply to level-ground ambulation in the MKIII suit within the given parameters described in Table 1 and Table 6. Once equipped with more information, advanced application of these models may help us understand the human factors of future EVA suits.

The preliminary models for RPE and GCPS used the same combination of independent variables as described in Equation 1, except that MR was replaced with RPE or GCPS as the dependent variable.

The method of least squares was used to estimate the parameters ($b_0 - b_4$) from the experiment data. Predictor variables used in the model were chosen (a) to produce as good a fit as possible with a minimum number of terms and (b) to contain reasonable biomechanical explanatory information. The parameter estimates are shown in Table 3. The R^2 for the RPE model was 0.804 and the root mean square error was 1.17. Figure 43 demonstrates the predictive accuracy for this model given the assumption that an RPE ± 1 is not noticeable to a subject. This assumption falls just under the root-mean-squared error of the model.

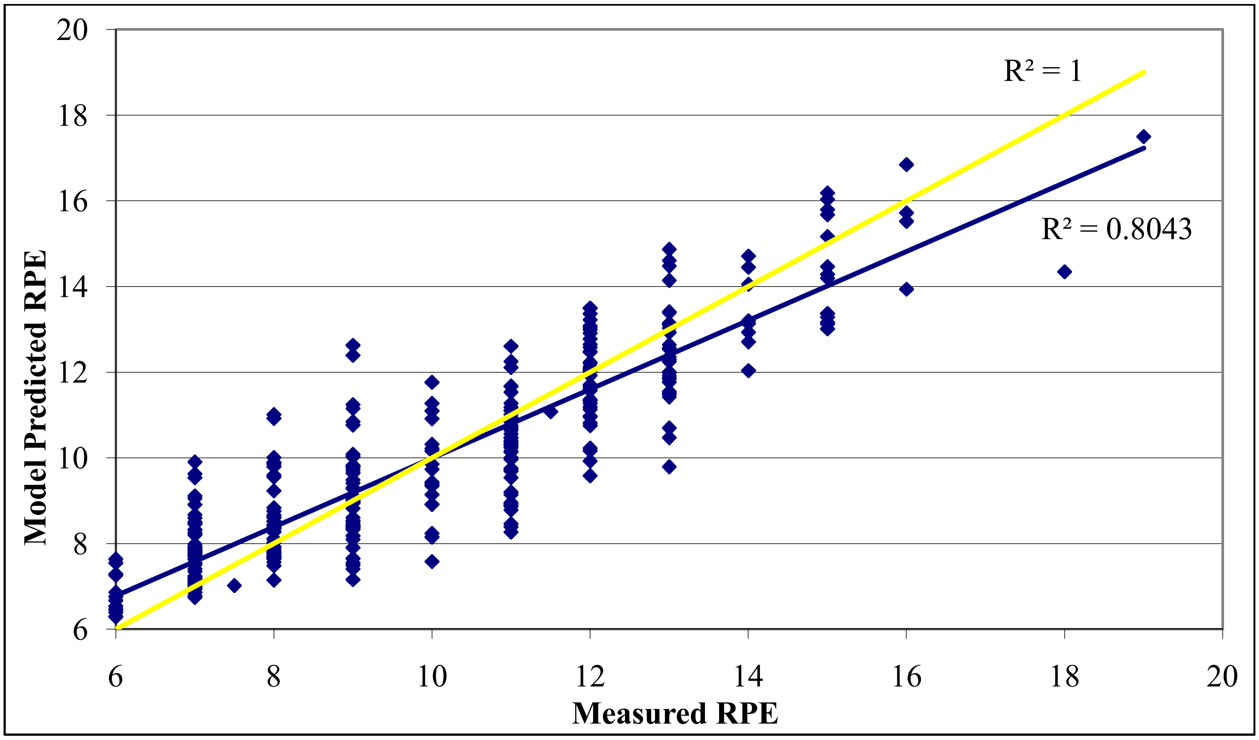

Figure 43. Difference between model predicted and measured RPE vs. speed for all suited data collection points.

Because the GCPS scale is not a continuous function, an ordered logistical regression model was selected to determine the probability of a known value given a set of inputs. For this type of model, the GCPS scale was broken down into three distinct categories: GCPS ratings of 1 to 3 were deemed "acceptable," ratings of 4 to 6 were deemed "modifications warranted," and ratings ≥7 were deemed "modifications required."

For example, consider an average male crew member of 82 kg and a 105-cm leg length in the reference configuration of the MKIII suit (121 kg and 29.6 kPa). Table 7 describes how speed affects the probability of GCPS ratings while keeping the subject, suit mass, and suit pressure constant.

Table 7. Probability of a Given GCPS Rating as a Function of Speed (Assuming: 82-kg subject, 105-cm Leg Length, 121-kg Suit/system Mass, 29.6-kPa Suit Pressure)

	GCPS Probability		
Level Ambulation Speed	**Acceptable**	**Modifications Warranted**	**Modifications Required**
0.75 $m \cdot s^{-1}$ (1.7 mph)	91%	9%	0%
1.25 $m \cdot s^{-1}$ (2.8 mph)	80%	20%	0%
1.75 $m \cdot s^{-1}$ (3.9 mph)	61%	38%	1%
2.25 $m \cdot s^{-1}$ (5.0 mph)	29%	69%	2%

Now assume a 1.25 m•s^{-1} translation speed. We can take the same male crew member (82 kg, 105-cm leg length) and maintain a constant pressure (29.6 kPa) but vary the suit mass. Table 8 describes the effect of varying the suit weight on GCPS ratings.

Table 8. Probability of a Given GCPS Rating as a Function of Suit Mass (Assuming: 82 kg Subject, 105-cm Leg Length, 29.6-kPa Suit pressure, 1.25 m•s^{-1} speed)

	GCPS Probability		
Suit Mass (kg)	**Acceptable**	**Modifications Warranted**	**Modifications Required**
63	87%	13%	0%
121	80%	20%	0%
186	69%	31%	0%
247	57%	43%	1%
308	43%	55%	1%

Because GCPS ratings were primarily in the acceptable or modifications warranted ranges for IST-1, the “modifications required” ratings will usually have a low probability based on this model. Future studies will provide additional data and more insight into all three ranges.

3.4.4 Predictive Model for Suit Kinematics

Predictive models also will be developed to predict the number of joint cycles and/or joint displacement across the ankle, knee, hip, and waist in the MKIII suit as a function of the properties of the suit, the anthropometry of the subject, and the speed of locomotion. These models will be developed as an example of the type of predictive model that can be built on and refined in greater detail as additional data are collected and analyzed to determine the number of cycles on any joint of the suit. These analysis tools will be effective for developing suit cycle requirements, and will provide significant cost savings during suit certification compared to the conventional methods of manual video tape review.

3.5 Secondary Test Objectives

3.5.1 Define Standard Measures and Protocols for Evaluating Exploration Suits and Requirements Verification

The protocols, instrumentation, and analysis techniques developed and applied for this test will be available for future testing of prototype Exploration suits. The body of knowledge for how to conduct both suited and unsuited testing on the POGO has been greatly expanded. Techniques never before used in biomechanical analysis are being applied to suited models. By refining data collection techniques and developing an understanding of which factors affect human performance in the suit and in reduced gravity, we will be able to combine these objective measurements with crew subjective comments to assess the performance of future Exploration suits.

3.5.2 Understand the Specific Human Performance Limitations of a Suit Compared to Matched Unsuited Controls

Comparisons of suited human performance in reduced gravity to unsuited human performance in both reduced gravity and Earth gravity is complex due to the equipment and analysis techniques necessary to accomplish this task. Comparisons of suited to unsuited metabolic rate, while performing the same tasks in lunar gravity, provide the basis for the estimate of the suit's metabolic cost. Although the systems in place for IST-1 allowed us to get preliminary data on this, the suspension methods of suited and unsuited subjects differ greatly. The metabolic cost of the suit results, as shown, is preliminary and would benefit from having an improved gimbal support system that suspends suited and unsuited subjects in the same way.

Metrics for comparing suited, reduced-gravity performance to Earth shirtsleeve performance include the ESSPI and the GCPS. The assumption behind both of these metrics is that Earth shirtsleeve performance is the target for ideal suited human performance in reduced gravity. GCPS was previously described in the subjective findings relevant to Sections 3.2 through 3.4.

Figure 44 demonstrates the ESSPI, defined in Section 2.4.3, as it relates to suited ambulation at lunar gravity with the MKIII in the POGO configuration of 121 kg and 29.6 kPa (4.3 psi). At slow walking speeds, the metabolic cost of lunar ambulation was approximately 1.5 to 3 times that of Earth shirt-sleeved ambulation; at speeds above 1.75 $m \cdot s^{-1}$, the metabolic cost of lunar running was lower than Earth shirt-sleeved conditions. This suggests that efforts to improve human performance while suited in 1/6-g need to be focused on the slower ambulation speeds, because performance at the faster speeds was already equivalent to 1-g shirtsleeve performance, which is considered the ideal target.

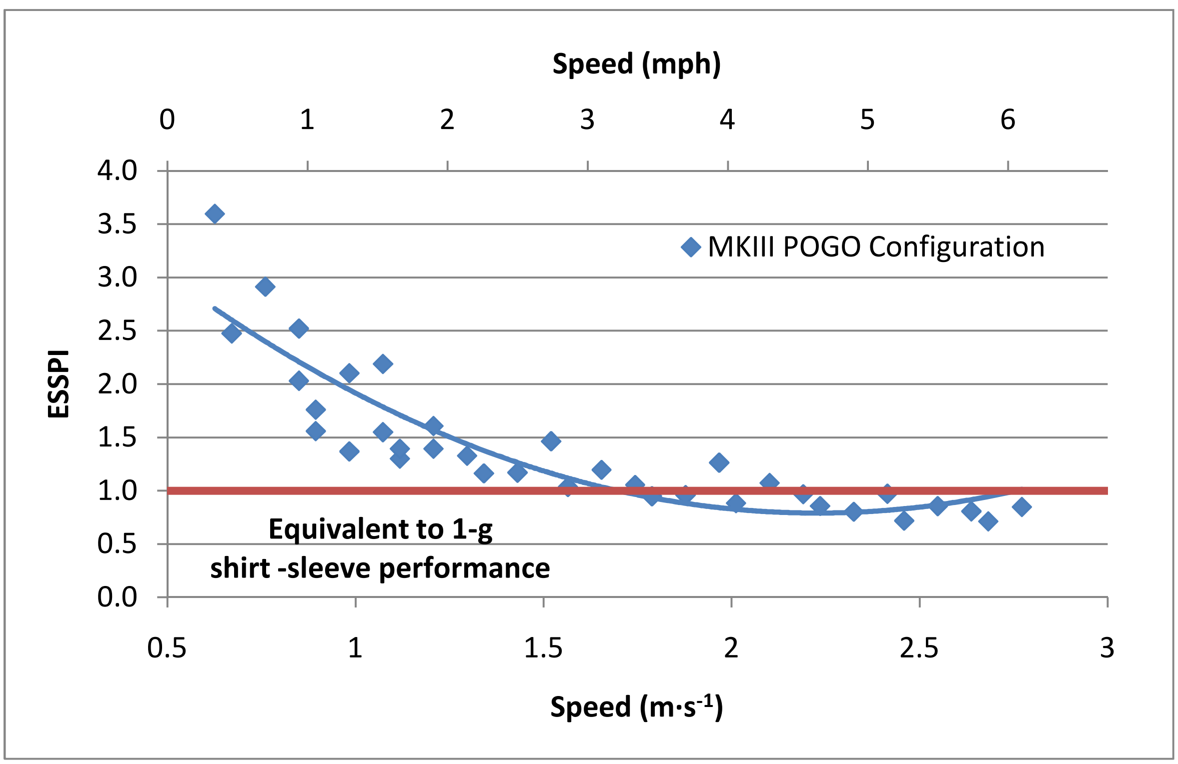

Figure 44. ESSPI for suited ambulation at lunar gravity with a 121-kg suit weight at 29.6 kPa.

Figure 45 shows the ESSPI as a function of gravity level. Equivalent performance to the 1-g shirtsleeve environment was only present at the two lowest gravity levels and at speeds greater than 1.5 m•s^{-1}. Current operational concepts indicate that most ambulation will be at slower speeds (<1.5 m•s^{-1}) and often at speeds less than 1.0 m•s^{-1}. Across all speeds, as weight increased, it was more difficult to achieve close to 1-g performance. While this may indicate that, for ambulation purposes, a lighter suit leading to a lower TGAW would bring performance closer to a 1-g shirtsleeve performance, it seems to make very little difference at the slower speeds.

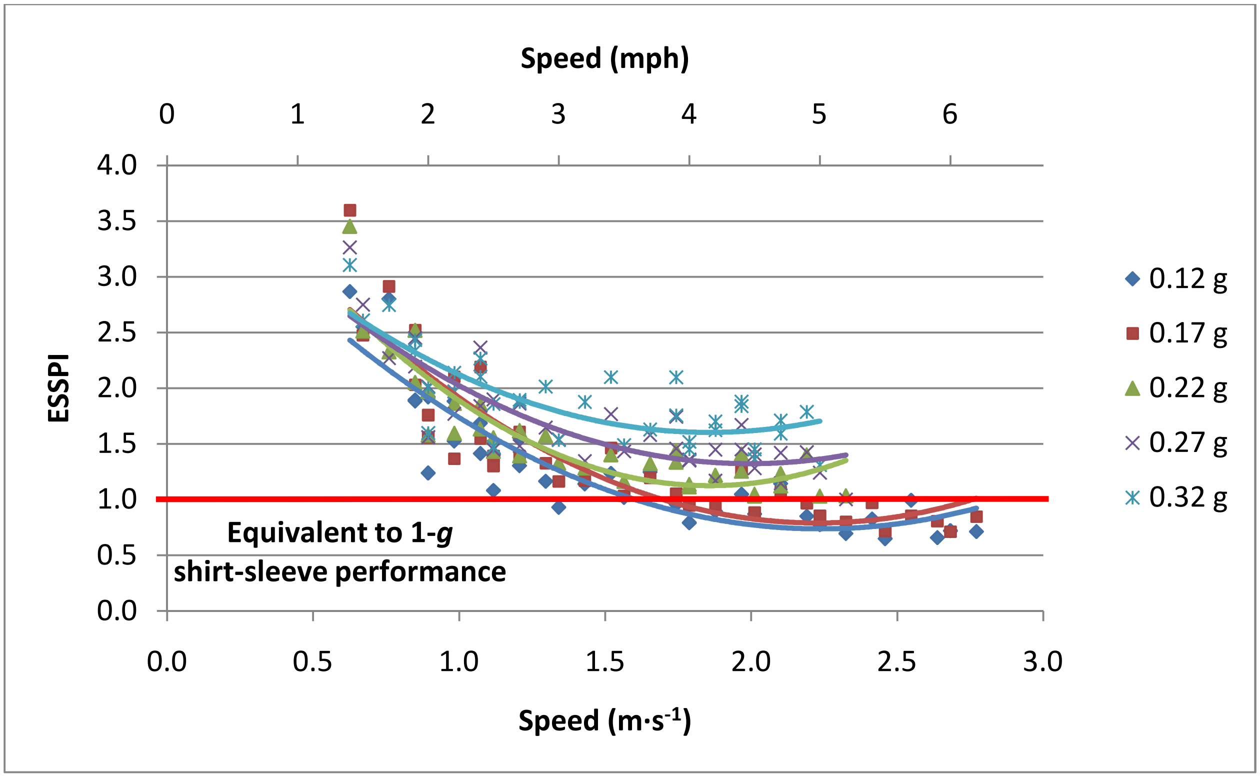

Figure 45. ESSPI vs. speed at different gravity levels during suited locomotion at a constant mass (121 kg) and pressure (29.6 kPa).

Finally, an understanding of how a subject moves differently in and outside of a suit is an important, and yet quite difficult, question to answer. One of the difficulties with this analysis is that the subject experiences a fair amount of travel within the suit before the suit actually moves. Some of the difficulties associated with quantifying the kinematic constraints that the suit imposes on human movement include differences between human kinematics and suit kinematics because of free space within the suit (see Figure 46), differences between suit joints/break points and human joint locations, and the fact that suit joint programming does not necessarily mimic human joint movement.

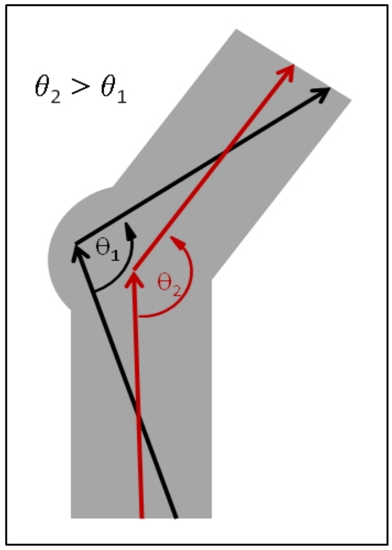

Figure 46. Example of the current difficulties with studying how the suit affects human movement (a possible suit knee angle is shown in red, and a possible human knee angle is shown in black)

3.5.3 Collect Metabolic and GRF Force Data to Develop an EVA Simulator for Use on Future Prebreathe Protocol Verification Tests

Data from this study and other studies of EVA and human performance in reduced gravity will be used to develop an EVA simulator for employment in the verification of prebreathe protocols. Four factors primarily affect the risk of decompression sickness: environmental pressure, time at reduced pressure, prebreathe time, and level of activity (14). Preliminary evidence suggests that as a defined level of activity using VO_2 may be more significant than previously thought (15), having an accurate and realistic simulation of EVA activities will help verify current and new prebreathe protocols. In addition to metabolic rate, GRF is also considered to be an important factor for which an EVA simulator should exercise control (16).

3.5.4 Provide Data to Estimate Consumables Usage for Input to Suit and PLSS Design

These data will be provided to the suit and PLSS team through development of a comprehensive model that would provide the ability to alter crew, suit, and EVA activity parameters to see what effect this would have on consumable usage, joint displacement, and crew member subjective ratings. Eventual development of these models depends on increasing the amount of data by testing more tasks, more subjects, and different suits in different lunar analog environments. Intermediate steps before the complete development of this model include providing inputs based on the data collected to date through test reports and data summary presentations.

3.5.5 Assess the Cardiovascular and Resistance Exercise Associated with Partial-gravity EVA for Planning Appropriate Exploration Exercise Countermeasures

To what extent lunar gravity and EVA will provide a countermeasure to the deconditioning of a crew member’s muscular, cardiovascular, and bone systems is poorly understood. Much has been learned through previous microgravity research on the development of effective exercise and non-exercise countermeasures, but the extent to which these lessons learned will be applicable in the lunar architecture is unknown. Data from this and other studies will provide the basis for the development of an EVA simulator that will not only allow for the verification of prebreathe trials, but will also allow for lunar bedrest studies and longitudinal human system modeling.

3.6 Study Limitations

Because this was a continuation of the EWT, one of the first questions to answer was to determine whether any differences between the EWT and IST-1 repeated measures existed. IST-1 had three subjects who had participated in the EWT and three new subjects. To look at the test-to-test variability, only the three returning subjects were compared. The only two carry-over conditions were suited at lunar gravity and 29.6 kPa (4.3 psi) and the unsuited lunar gravity weight-matched (121-kg suit mass) control trial. Figure 47 compares these test conditions. When comparing results, the suited metabolic rates from IST-1 were consistently lower than those of EWT. The unsuited metabolic rates were not significantly different. Proposed reasons for this variation include increased subject familiarization with partial-gravity ambulation, a larger treadmill walking surface, and improved weigh-out procedures where each subject's weight on the ground was measured by force plates to within 1.4 kg of the target weight. Previous weigh-out procedures relied only on a load cell measuring POGO off-loading force.

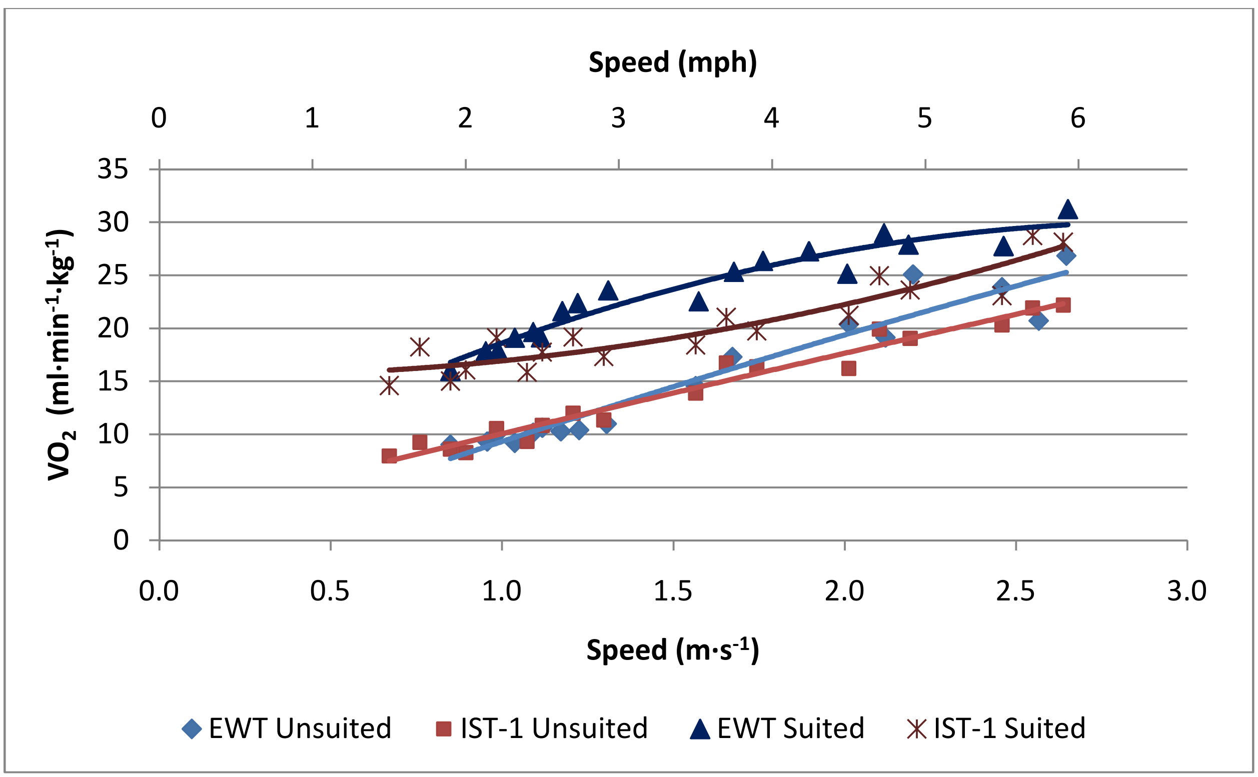

Figure 47. Lunar locomotion comparison of repeat subjects from both the EWT and the IST-1. Suited data refer to the MKIII in the POGO configuration (121-kg suit mass and 29.6 kPa) at lunar gravity. Unsuited data refer to the 121-kg weight-matched condition.

This study was a continuation of the work started with the EWT, and many of the same limitations still exist (1). Limitations pertinent to this study are as follows: Trials in this study were performed on a smooth, firm treadmill surface while a portion of the subject's weight was lifted by a servo-controlled device that limited movement degrees of freedom. Development of simulators that permit more realistic ambulation on planetary surfaces will be required to test a full battery of EVA-like tasks and timeline simulations.

The results of this study are based on level-ground treadmill ambulation data from six male subjects in the MKIII suit. How representative these subjects are of the total astronaut population is not fully quantified, but some representative figures are shown in Appendix C. As these studies progress and, eventually, when new prototype suits are tested, every effort should be made to include as many subjects as possible as well as to characterize the subject pool's fitness and anthropometry so that an understanding can be reached of the factors that contribute to improved performance.

A significant limitation of the suited gimbal system was the inability to precisely control or accurately set the gimbal center of rotation in relation to the total system CG. Standard procedures were used to configure the systems such that subjects were suspended in a neutral posture while in the suit before adjusting to their preferred position. All subjects freely chose to align the gimbal center of rotation slightly forward and low to the position of the system CG. Improved designs of the gimbal system will be required to allow precise and consistent application of CG alignment and to permit systematic variation of CG locations to study the effects of CG on human performance.

Although TGAW was varied in the suited varied-weight trials, inertial mass was not varied. All varied weights occurred at a suit mass of 121 kg. Without having the actual mass needed to achieve the correct TGAW in lunar gravity or characterizing the effects of mass independently, the results of the varied-weight section have to be viewed as preliminary.

All predictive models need to be regarded as preliminary as the data set is not fully crossed and possible inter-relationships that are not yet understood may exist among pressure, gravity, and mass.

Another consideration is that during the reduced-gravity trials, the subjects' arms and legs still operated in a 1g field. Because the weight of their limbs was not reduced, it is possible that the metabolic and biomechanical data may not accurately simulate the weight that would occur in true reduced-gravity environments. One possibility is that human limbs are generally used in an ROM (cosine of the angles) in which gravity has a reduced effect; therefore, most of the energy expended is for force generation and limb velocity. Finally, unsuited data collected in actual lunar gravity during parabolic flight indicate that the walk-run transition speeds during parabolic flight were similar to those found on the POGO (17). These findings suggest that the locomotive patterns used during POGO tests led to the same general walk-run transition speeds and, thus, may be representative of those that would be used in an actual lunar gravitational environment.

3.7 Lessons Learned

Extended familiarization time, both suited and unsuited, was allowed for all subjects. This may have accounted for some of the differences between the EWT and IST-1 metabolic rates. Every effort should be made in future studies to allowed extended familiarization time, possibly including full familiarization trials, to negate a learning effect from start to finish on the dependent variables tested.

The larger treadmill belt width and length was appreciated by subjects who had experience using the smaller treadmill from the EWT.

Reduced-gravity weigh-out procedures were improved using the suit/subject/system's static weight on the ground as the target. Force plates in the treadmill were summed to provide this weight, but this process took longer than subjects would have preferred.

Near the end of suited data collection trials, a thermal data collection system was integrated into the suit system cooling loop. Data capability included LCG flow rate, inlet/outlet temperatures, and outlet relative humidity. This system will eventually provide data to understand other ways of calculating metabolic rate as well as to provide inputs and feedback to bioadvisory algorithms, which may play an important role in providing feedback for exploration crew members.

As described previously, subject speeds during ambulation were based on individual's PTS. Initially, this was done so that walking and running could be compared across different gravities independent of speed. Given that distinctions between walking and running seem to be less clear in reduced gravity, it may be beneficial to switch to fixed speeds for future tests. Also, having individual speeds did not allow for direct comparison between conditions and subjects.

For this study, a specific gait was not prescribed; subjects were instead directed to maintain a consistent gait throughout the biomechanics data collection period of each trial. While this eliminated most of the problems of gait change affecting biomechanical data collection, it did complicate data analysis because gait style significantly impacted many biomechanical metrics. In future tests, subjects may possibly be instructed to employ a symmetric, Earth-like gait throughout the study even if an asymmetric gait is favored. Future studies also could examine how changing gait affects results.

The unsuited harness was improved from a comfort standpoint, although leg ROM may have still been affected. The kite-surfing harness provided greater surface area in contact with the portion of the subject's body being lifted, and the use of neoprene shorts provided another layer of padding.

Having an accurate unsuited 1-g baseline is critical to many analyses, including the ESSPI and the GCPS. Because this study was ambulation-based and unsuited Earth-based ambulation is widely studied and referenced, we did not include a 1-g unsuited condition. We also felt that as subjects had enough experience walking in 1-g, they would have a valid reference point for GCPS comparisons. While this may not have negatively affected GCPS ratings, this choice resulted in very limited metabolic and biomechanics data for subjects in 1-g to which to compare any data objectively. Population norms may be good reference points, but they are not sufficient for a direct condition-to-condition comparison for a given subject. All future reduced-gravity, planetary surface-based studies are highly encouraged to include an unsuited 1-g condition for every subject.

4 CONCLUSIONS

4.1 Contributions of Weight, Mass, Pressure, and Suit Kinematics to Metabolic Cost of MKIII in POGO Configuration

By varying suit pressure and system weight, we have been able to identify the portion of metabolic rate specifically related to those components as well as to define the residual cost associated with the combined effects of suit mass, suit kinematics, stability, and suited/unsuited system harness differences for the MKIII suit in its POGO configuration (121 kg [265 lb], including mass of PLSS mockup and gimbal, 29.6 kPa [4.3 psi]) during lunar ambulation.

At the lowest speeds, the weight of the suit/system had no effect on metabolic rate; but as speed increased, the metabolic cost of weight steadily increased, reaching 14% of the total metabolic cost and accounting for approximately 35% of the metabolic cost of the suit at the three highest speeds. Pressure-volume metabolic work was fairly consistent across the four middle speeds at 15% of total metabolic cost and approximately 38% of the suit's metabolic cost. The remaining suit- and system-related factors (mass, suit kinematics, stability, and harnessing differences) were the most variable component, steadily decreasing in absolute and relative terms through the first five speeds from 41% to 10% of the total metabolic cost, but promptly increasing at the fastest speed. Full results are shown in Figure 12 and Figure 13.

Future tests will determine individual contributions of these remaining components as well as examine various interrelationships and coupling factors present in untested combinations of these variables. By understanding the individual factors, we will be able to provide specific recommendations for suit design requirements, EVA mission planning, and overall consumables packaging.

4.2 Effects of Varied Weight, Mass, and Pressure on Suited Human Performance

Initial findings suggest that for level-ground ambulation, suit pressure minimally influences metabolic rate, biomechanics, or subjective assessments of exertion and operator compensation for the group as a whole. However, some evidence, based on different metabolic profiles between subjects (Figure 15), indicates pressure may be important within individual subjects for level-ground ambulation.

The observation that metabolic rate was essentially unchanged by suit pressure is supported by the suit elements description of the MKIII suit as constant volume. Different suit designs, with dissimilar joint designs and sequencing, might be affected in another way by suit pressure, especially if constant volume joints are changed to soft joints. These observations, which are limited to ambulation, do not imply that suit pressure would not significantly affect crew members performing upper body- and hand-intensive exploration tasks.

Initial findings show no consistent trend between added mass variations of 0 to 34 kg and metabolic rate in the unsuited condition. However, it is possible that this is a result of hardware limitations. Modifications to the spider gimbal system to accommodate shirt-sleeved subjects should provide a better platform to investigate the effects of mass in future tests.

Gravity level does exert a large effect on performance. At this point, we hypothesize that much of the change in performance occurs because of the difference in TGAW. At the two slowest speeds, this change in weight did not affect average metabolic rate. At faster speeds, the differences became significant, reaching up to approximately 15 $mL•kg^{-1}•min^{-1}$ at the fastest speeds between gravity levels of 0.12-g and 0.32-g. Based on an analysis of oxygen transport costs, which can be thought of as the human equivalent of gas mileage, we suggest that a suit mass of 186 kg or less may be necessary for an efficient performance in a 10-km walkback contingency; the most efficient walkback speed for a 186 kg suit might be 1.4 to 2.1 $m•s^{-1}$, and the most efficient walkback speed for a 63- to 121-kg suit might be 1.8–2.6 m•s^{-1}, although many factors may affect this selection including cooling limitations (1), terrain (10), and an understanding of how alike a change in TGAW from just an alteration in weight represents a true change in suit mass.

The metabolic cost of the suit, unrelated to weight, was tied to speed. At slower walking speeds, there was little to no increase as gravity increased; but with faster walking and running speeds, an increase as gravity level increased was clearly shown. This indicates that interactions between weight and speed exist that were not fully understood and are not consistent across the whole range of ambulation speeds.

Perceived exertion increased as gravity increased and the increase in exertion with speed was greater at higher gravity levels. For all subjects at all speeds, gravity levels ≤0.22-g had GCPS ratings ≤5, with most in the acceptable range of ≤4. In many cases, the heavier weights were also acceptable, but there were several ratings ≥6, especially at higher speeds.

Biomechanical data, as would be expected, showed an increase in stance time, cadence, and peak vertical ground-reaction force with an increase in weight and speed. These changes, with increases in both speed and weight, demonstrate that the amount of work done by the subject is also increasing. Biomechanical data also showed little difference with changes in pressure. This is also to be expected for a near-constant-volume suit with pressure regulation. Unless a suit experiences a dramatic buildup of internal pressure, no mechanical changes in the suit should affect performance. Interpretation of joint ROM data was limited because of anomalous findings. These anomalies were found at a specific gravity and pressure, suggesting a complex and unexpected relation with the system at those conditions.

4.3 Comparison of Locomotion in the MKIII at POGO Configuration to MKIII with the Waist Bearing Locked

Metabolic data indicate that locking the MKIII waist bearing did not affect metabolic rate during level-ground ambulation. However, subjective ratings did differ between conditions, with the average RPE slightly higher and the GCPS ratings approximately one to two levels higher in the waist-locked condition than in nominal operations. Interpretation of biomechanical differences was limited to the high variability of gait selection within and between subjects.

4.4 Predictive Models of Metabolic Rates, Subjective Assessments, and Suit Kinematics

A preliminary, multiple linear regression model was developed to predict the metabolic cost of locomotion in the MKIII suit as a function of the suit properties, the subject's anthropometry, and the speed of locomotion. This model, while preliminary and descriptive in nature, highlights the possible applications for a complete model including: refining operational concepts, defining suit requirements, and predicting consumable usage. Separate models to predict RPE and the probability of a given GCPS rating were also developed. Models to determine joint cycles and other lifecycle aspects of the suit are in progress. Eventually, with the inclusion of additional data and improved understanding of various interrelationships, these models will be combined into an all-inclusive predictive algorithm, which would provide one comprehensive, user-friendly tool that would incorporate the results of applicable human performance testing in reduced gravity.

4.5 Secondary Objectives

This test series provides an ideal opportunity to use the collected data for much more than addressing specific primary objectives. Lessons learned from this test can be used to better testing technology and lunar analog environments as well as to prepare for future testing and requirements verification of EVA suit candidates. Data will be used to develop an EVA simulator for use on prebreathe protocol verification and exercise countermeasure studies. Metrics to compare suited to unsuited performance in both reduced and Earth gravity will help provide a reference point to determine what ideal suited human performance entails. A key application of this study was to further the knowledge of suited human performance. While this has direct application to certain questions that are currently being looked at, it will undoubtedly help direct the questions formulated in the future as well.

4.6 Summary

IST-1, which addressed the primary objectives of the study, has begun to provide some data to answer secondary objectives. As more studies are completed, these predictive models, suit parameter interrelationships, standard measures and new metrics such as ESSPI will become complete products allowing for evidence-based recommendations to optimize suit design and plan EVA operational constraints and consumable targets.

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Appendix A: Submaximal Test Termination Criteria

Test Termination Criteria for All Submaximal Testing

1. Subject request to stop at any time
2. Subject's heart rate or measured VO_2 at level >85% VO_2pk for 2 min or more
3. Failure of POGO hardware and/or treadmill system

ADDITIONAL Test Termination Criteria for Suited Submaximal Testing

1. Expired CO_2 levels >5%
2. If subject reports discomfort rating ≥7 (on 10-point scale) for two consecutive recording periods, subject will be asked to terminate the test. If subject asks to continue, he/she will be allowed to continue until condition 3 is met
3. Discomfort rating ≥7 for three recording periods (may be nonconsecutive) or severe pressure point
4. Engineering hardware failure such as in suit or suit environmental control (These standard/approved engineering termination criteria were described in the detailed test plan (CTSD_AHI_0009) and addressed in the test readiness review.)

Appendix B: Ratings Scales for Subjective Measures

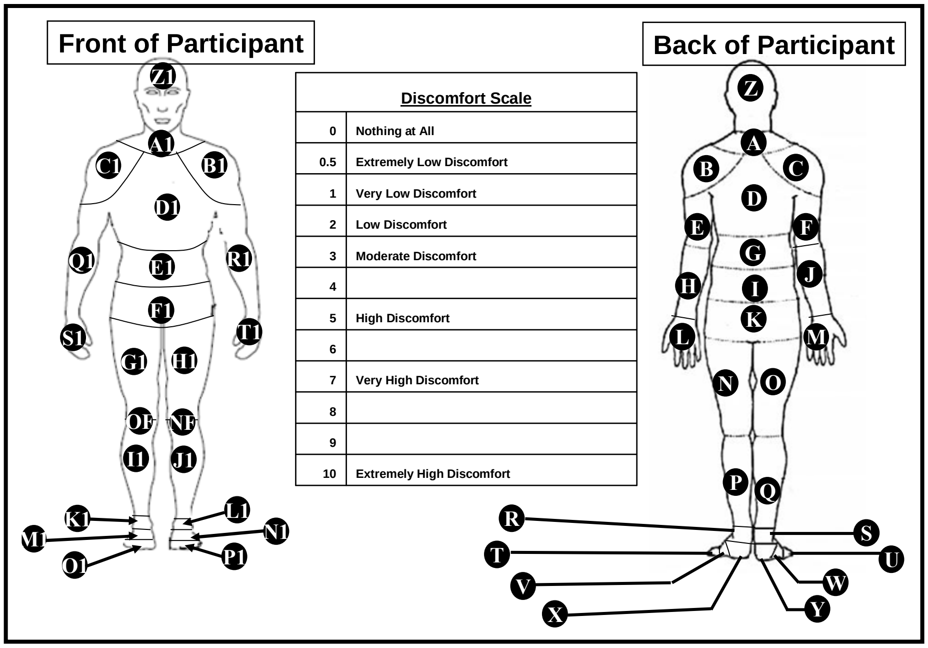
Gravity Compensation and Performance Scale

1	**Excellent** – easier than 1g
2	**Good** – equivalent to 1g
3	**Fair** – minimal compensation for desired performance
4	**Minor** – moderate compensation for desired performance
5	**Moderately objectionable** – considerable compensation for adequate performance
6	**Very objectionable** – extensive compensation for adequate performance
7	**Major deficiencies** – considerable compensation for control; performance compromised
8	**Major deficiencies** – intense compensation; performance compromised
9	**Major deficiencies** – adequate performance not attainable with maximum tolerable compensation
10	**Major deficiencies** – unable to perform task

Borg Rating of Perceived Exertion (RPE) Scale

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Corlett and Bishop Discomfort Scale



Bedford Thermal Scale

–3	Much Too Cool
–2	Too Cool
–1	Comfortably Cool
0	Comfortable
1	Comfortably Warm
2	Too Warm
3	Much Too Warm

Thermal Preference

–2	Much warmer
–1	A Bit Warmer
0	No Change
1	A Bit Cooler
2	Much Cooler

Appendix C: Subject Comparison to General Astronaut Population

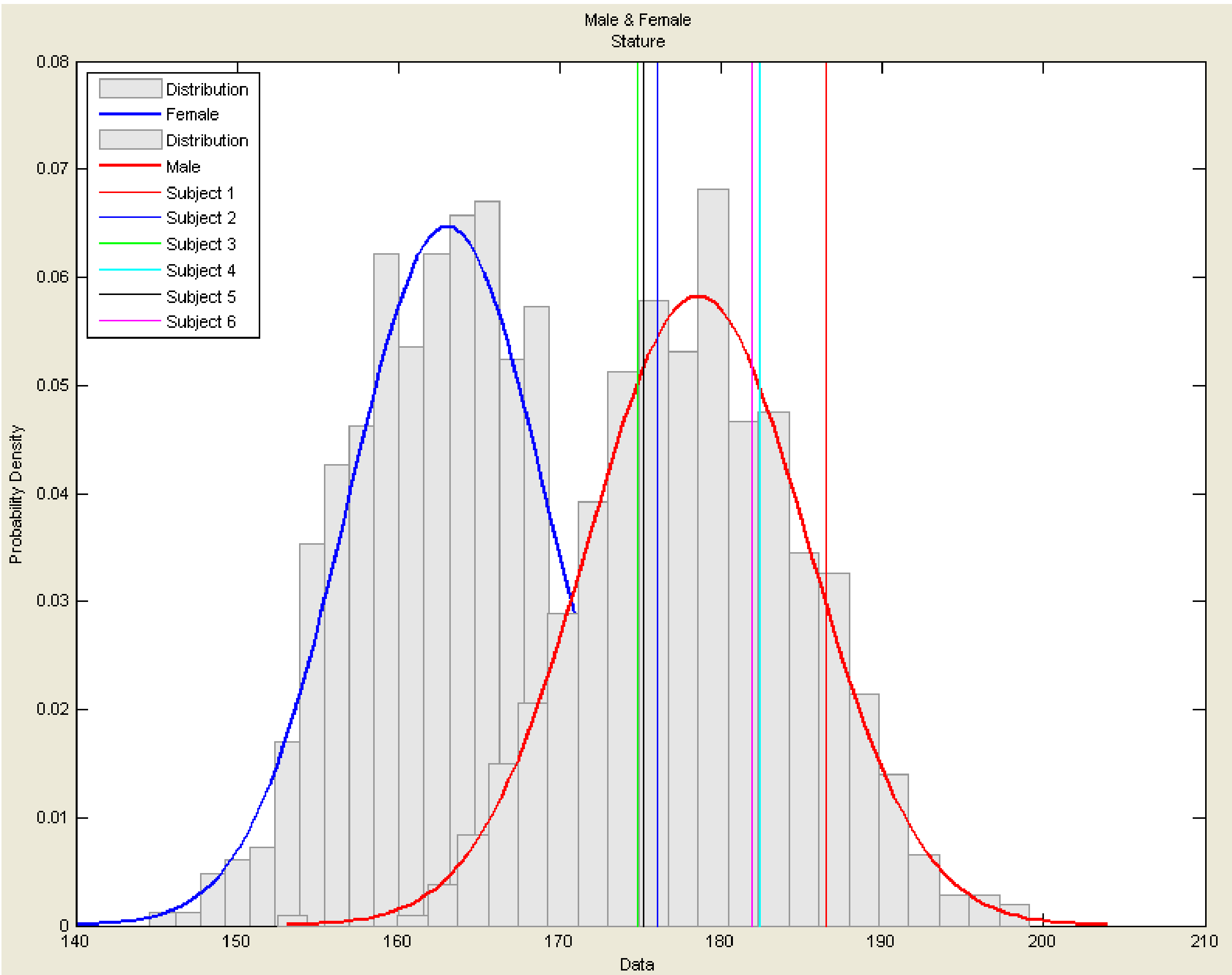


Figure 48. Distribution of IST-1 subject height in relation to the astronaut population.

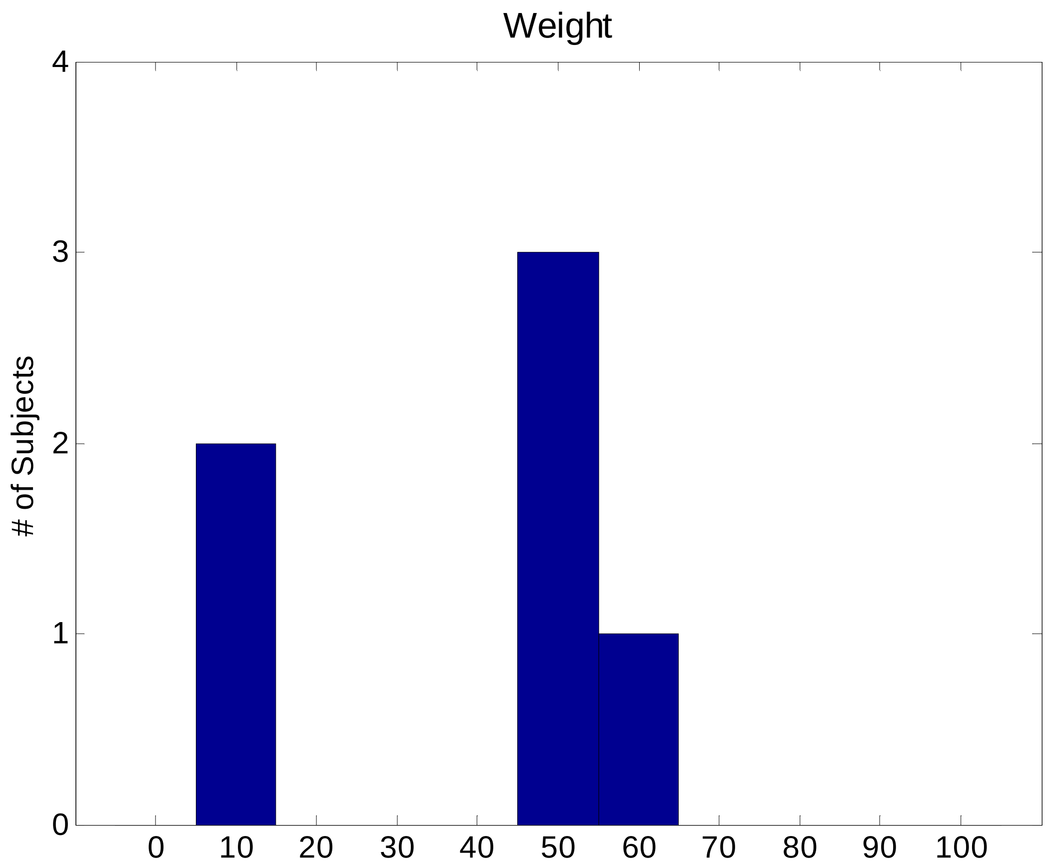


Figure 49. Distribution of IST-1 subject body mass in relation to the astronaut population.

Appendix D: Initial IST-1 Quick-Look Report

EVA Systems Project FY07 [Fiscal Year 2007] SE&I [Systems Engineering and Integration] Test 1 Quick-look Test Report

To:	EVA Systems Project Test and Facilities, Manager/Jeff Patrick EPSP Manager/Mike Gernhardt EPSP Test Lead/Jason Norcross
From:	EVA Systems Project Test and Facilities, Test Lead/Jessica Vos ESCG EVA Test Team / Kevin Rullman
Date:	August 7, 2007
Subject:	EVA System Project FY07 SE&I Test 1 Quick-look Report

Objectives

Phase I: Measure the transport costs of inertial mass (shirtsleeve only) during lunar ambulations.
- Add mass to the subjects while controlling the POGO system to maintain a constant weight

Phase II: Measure the effects of varied suit pressure during lunar ambulations.
- Constant mass and weight (or POGO offloading)
- 1.0, 3.0, 4.3, 5.0, and 6.5 psi

Phase III: Measure the effects of varied suit weight (or POGO offloading) during lunar ambulations.
- Constant mass and pressure
- 0.12g, 0.17g, 0.22g, 0.27g, and 0.32g equivalent offloading

Dates Performed: March 20 – July 24, 2007

This memo serves to document the testing accomplishments for the EVA Systems Project FY07 SE&I Test 1 conducted March 20 – July 24, 2007. This report does not provide formal Constellation EVA Systems Project or EPSP recommendations or conclusions. A complete technical report documenting the EVA Systems Project and EPSP recommendations stemming from this test will be forthcoming following review of test data. The test team observations provided in this report should be taken as initial indicators of results only and are not to be used for EVA Systems Project or EPSP recommendations.

General Summary

The EVA Systems Project FY07 SE&I Test 1 was performed at the SVMF at JSC. This was an integrated test jointly performed by the Constellation EVA Systems Project and the Human Research Program's EPSP. The purpose of this test was to collect human performance data (metabolic, human kinematics, thermal, subjective comfort, etc.), given variations in suited operating pressure and suited weight for lunar ambulation tasks. Committee for the Protection of Human Subjects (CPHS) approval for this test activity was obtained on February 22, 2007. Two test readiness reviews, one chaired by

Craig Dinsmore from the Space Suit Systems Branch (EC5) and the other chaired by Arne Aamodt from SVMF (DX14), were held before the start of this test series.

Three separate "engineering runs" were successfully conducted with subjects from the JSC Engineering Directorate to verify the data-collection methods for each of the three phases of testing listed above. A total of six primary test subjects (selected from the current NASA Astronaut Corps) completed each phase of the test, which consisted of two suited test days and one unsuited (shirtsleeve) test day. The three different test days (or phases) were not required to be performed in any particular order. Test subject schedules, suit availability, and test area configuration mostly dictated the day-to-day testing order. An average test day, in shirt sleeves or suited, consisted of approximately 4.5 hours of testing. All testing was completed with only a few hardware anomalies and/or test related delays, detailed in the section entitled "Hardware Anomalies and Test Related Delays."

Test Equipment

POGO, MK III Suit, and Shirtsleeve Harness

The three phases of this test used the Partial Gravity Simulator (a.k.a. "POGO") as the primary weight relief system for the test subjects in both the shirtsleeve and the suited configurations. POGO's pneumatic piston was attached to the MKIII suit via the Spider Gimbal System, which allowed for limited rotational movement by the suited subject in the roll, pitch, and yaw axes while attaching to the volumetric PLSS mock-up located on the hatch of the MKIII HUT. The POGO weight relief was varied during this test to emulate varied EVA system weights (referred to in this report as difference in gravity levels). For the shirtsleeve configuration (with the weighted X-Vest), the POGO piston attached to a spreader bar that distributed the offloading force to the body restraint harness via four straps (two on each side). Suited tests required the use of certified breathing air, for which the SVMF brought a tube trailer online soon after the test series began to alleviate the large number of K-bottles required for each test. The tube trailer greatly reduced the logistical management of the breathing air supply for JSC, which became an issue after the EWT in June 2006 and threatened the schedule for this test series as well.

Treadmill and Force Plates

Subjects ambulated on the newly acquired VacuMed research treadmill (model no. 13610), which provided a much larger surface area for translating and functioned as intended throughout the test. As a custom design modification, four AMTI force platforms (model no. OR6-5-2000) were installed by the vendor before delivery of the treadmill to accommodate our data collection needs. GRF data waere captured at 1,000 Hz. For more information regarding the COTS [commercial off-the-shelf] treadmill design, please refer to the following Website: http://www.vacumed.com/zcom/product/Product.do?compid=27&prodid=688.

Communications

Both wireless and hardwired communication systems were used at various stages in the test. The wireless system used at the beginning of the test was on loan from the CTSD [Crew and Thermal Systems Division] Systems Test Branch (EC4) and had to be returned mid-test, at which point it was replaced with the hardwire system (owned by EC5). Although the hardwire system proved to be sufficient, the wireless system was preferred over the hardwired system because of the mobility requirements of many of the critical test personnel inside the test area and the improved safety aspects resulting from reductions in wires spanning the test floor area.

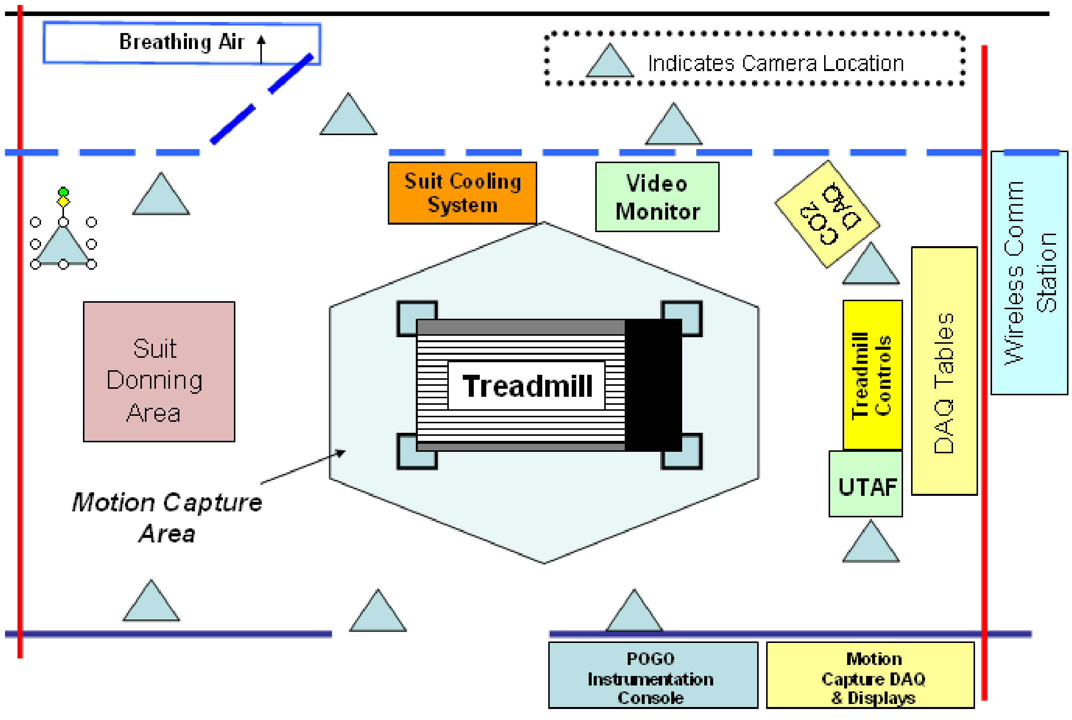
Motion Capture System
A Vicon MX40+ system, with 12 cameras total, captured video at 100 Hz using near-infrared (IR) strobes (essentially the same wavelength as the older system used in the Walkback test in June 2006) and 4-megapixel sensors. Vicon Nexus software was used for motion capture and reconstruction of motion and GRF data.

Metabolic Rate and Heat Load Data Collection
For the shirtsleeve tests, each subject's metabolic rate was determined from the continuous measurement of VO_2, CO_2 production, and V_E using a headset/mouthpiece connected to a TrueOne® 2400 metabolic cart from ParvoMedics (Sandy, Utah). During exercise in the MKIII suit, metabolic rate was calculated using the following variables: measured suit ventilation rate; expired CO_2 concentration in the exhaust umbilical (captured via a CD-3A IR CO_2 analyzer from AEI Technologies, Pittsburg, Pa.); and the regression between VCO_2 and VO_2 as measured during each subject's VO_2 peak test. This technique and hardware were identical to those currently used during suited NBL test and training activities.

Heart rate was measured from a Polar USA (Lake Success, N.Y.) heart rate monitor for both shirtsleeve and suited test configurations.

Cooling water temperatures were measured at both the inlet and outlet of the LCG and the outlet of the cooling cart (which had been newly remodeled to handle a greater heat load after the Walkback Test) during suited test activities. These temperate data provided an indication of the heat load being produced by the each subject (and removed by the LCG) for each suited test.

Test Area Layout Diagram (POGO Area of SVMF, B9 High Bay)



Test runs completed per date are as follows:

22-Mar				
	Varied Pressure			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
11:18:00	1.7 to 5.7 mph	3.0 psi	1/6-g	Suited
11:45:30	1.7 to 5.7 mph	5.0 psi	1/6-g	Suited
12:22:00	1.7 to 5.7 mph	6.5 psi	1/6-g	Suited

27-Mar				
	Varied Pressure			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:45:30	1.9 to 5.9 mph	0 psi	1/6-g	Suited –- no helmet
10:44:00	1.9 to 5.9 mph	3.0 psi	1/6-g	Suited
11:15:38	1.9 to 5.9 mph	5.0 psi	1/6-g	Suited
11:48:20	1.9 to 5.9 mph	6.5 psi	1/6-g	Suited

4-Apr				
	Varied Weight			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:24:24	1.7 to 5.7 mph	4.3 psi	0.12-g	Suited
9:59:00	1.7 to 4.7 mph	4.3 psi	0.32-g	Suited
11:14:18	1.7 to 4.7 mph	4.3 psi	0.27-g	Suited
11:42:22	1.7 to 5.7 mph	4.3 psi	1/6-g	Suited
12:13:27	1.7 to 4.7 mph	4.3 psi	0.22-g	Suited
12:38:30	1.7 to 5.7 mph	1.0 psi	1/6-g	Suited
1:02:27	1.7 to 5.7 mph	4.3 psi	1/6-g	Suited – waist locked

11-Apr				
	Varied Pressure			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
10:11:52	2.0 to 6.0 mph	5.0 psi	1/6-g	Suited
10:44:48	2.0 to 6.0 mph	4.3 psi	1/6-g	Suited
11:11:10	2.0 to 6.0 mph	3.0 psi	1/6-g	Suited
11:37:25	2.0 to 6.0 mph	1.0 psi	1/6-g	Suited
Did Not Finish (DNF)	DNF	DNF	DNF	suit malfunction – see section below for details

12-Apr				
	Varied Pressure			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
2:07:08	1.5 to 5.5 mph	1.0 psi	1/6-g	Suited
2:30:40	1.5 to 5.5 mph	3.0 psi	1/6-g	Suited
2:54:35	1.5 to 5.5 mph	6.5 psi	1/6-g	Suited
3:21:45	1.5 to 5.5 mph	4.3 psi	1/6-g	Suited
3:47:02	1.5 to 5.5 mph	5.0 psi	1/6-g	Suited

17-Apr				
	Varied Weight			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:21:00	1.5 to 5.5 mph	4.3 psi	0.12-g	Suited
9:48:30	1.5 to 4.5 mph	4.3 psi	0.27-g	Suited
10:26:45	1.5 to 4.5 mph	4.3 psi	0.22-g	Suited
10:56:30	1.5 to 4.5 mph	4.3 psi	0.32-g	Suited
11:23:30	1.5 to 5.5 mph	4.3 psi	1/6-g	Suited - waist locked

18-Apr				
	Varied Weight			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:16:24	1.9 to 4.9 mph	4.3 psi	0.32-g	Suited
9:54:10	1.9 to 4.9 mph	4.3 psi	0.22-g	Suited
10:31:25	1.9 to 5.9 mph	1.0 psi	1/6-g	Suited
10:59:15	1.9 to 5.9 mph	4.3 psi	0.12-g	Suited
11:30:34	1.9 to 4.9 mph	4.3 psi	0.27-g	Suited
12:01:18	1.9 to 5.9 mph	4.3 psi	1/6-g	Suited
12:27:15	1.9 to 5.9 mph	4.3 psi	1/6-g	Suited – did not complete final speed

19-Apr				
	Varied Weight			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
13:15:05	2.0 to 5.0 mph	4.3 psi	0.22-g	Suited
13:53:45	2.0 to 5.0 mph	4.3 psi	0.32-g	Suited
14:49:10	2.0 to 6.0 mph	4.3 psi	0.12-g	Suited
15:30:07	2.0 to 5.0 mph	4.3 psi	0.27-g	Suited
16:01:02	2.0 to 6.0 mph	6.5 psi	1/6-g	Suited

26-Apr				
	Varied Pressure			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
9:55:47	1.4 to 5.4 mph	6.5 psi	1/6-g	Suited
10:24:30	1.4 to 5.4 mph	5.0 psi	1/6-g	Suited
11:08:21	1.4 to 5.4 mph	3.0 psi	1/6-g	Suited
11:33:50	1.4 to 5.4 mph	1.0 psi	1/6-g	Suited

27-Apr				
	Varied Weight			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
8:53:00	1.4 to 5.4 mph	4.3 psi	1/6-g	Suited
9:46:20	1.4 to 4.4 mph	4.3 psi	0.32-g	Suited
10:30:45	1.4 to 4.4 mph	4.3 psi	0.27-g	Suited
10:54:30	1.4 to 4.4 mph	4.3 psi	0.22-g	Suited
11:31:00	1.4 to 5.4 mph	4.3 psi	0.12-g	Suited
12:19:00	1.4 to 5.4 mph	4.3 psi	1/6-g	Suited

8-May				
	Varied Mass			
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
9:42:45	1.7 to 5.7 mph	1/6-g Weighted		Shirtsleeve
10:14:11	1.7 to 4.7 mph	0.27-g Weighted		Shirtsleeve
10:58:44	1.7 to 5.7 mph	1/6-g Weighted	25 lb	Shirtsleeve
11:34:45	1.7 to 5.7 mph	1/6-g Weighted	50 lb	Shirtsleeve
12:07:15	1.7 to 5.7 mph	1/6-g Weighted	75 lb	Shirtsleeve

9-May				
	Varied Mass			
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
9:19:52	2.0 to 6.0 mph	1/6-g Weighted	75 lb	Shirtsleeve
9:55:51	2.0 to 6.0 mph	1/6-g Weighted	50 lb	Shirtsleeve
10:28:19	2.0 to 5.0 mph	0.27-g Weighted		Shirtsleeve
11:01:14	2.0 to 6.0 mph	1/6-g Weighted		Shirtsleeve
11:40:37	2.0 to 6.0 mph	1/6-g Weighted	25 lb	Shirtsleeve
12:14:45	2.0 to 5.0 mph	0.32-g Weighted		Shirtsleeve

10-May				
	Varied Mass			
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
14:41:00	1.5 to 5.5 mph	1/6-g Weighted	50 lb	Shirtsleeve
15:21:50	1.5 to 5.5 mph	1/6-g Weighted	25 lb	Shirtsleeve
16:10:41	1.5 to 5.5 mph	1/6-g Weighted	75 lb	Shirtsleeve
16:46:55	1.5 to 4.5 mph	0.27-g Weighted		Shirtsleeve
17:24:24	1.5 to 5.5 mph	1/6-g Weighted		Shirtsleeve

15-May				
	Varied Mass			
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
9:13:00	1.9 to 5.9 mph	1/6-g Weighted	25 lb	Shirtsleeve
9:54:49	1.9 to 5.9 mph	1/6-g Weighted		Shirtsleeve
10:32:31	1.9 to 5.9 mph	1/6-g Weighted	50 lb	Shirtsleeve
11:06:20	1.9 to 5.9 mph	1/6-g Weighted	75 lb	Shirtsleeve
11:43:32	1.9 to 4.9 mph	0.27-g Weighted		Shirtsleeve

17-May				
	Varied Mass			
Start Time	Speed	Gravity Level	Added Mass	Conditions/Notes
8:59:41	1.4 to 4.4 mph	0.27-g Weighted		Shirtsleeve
9:34:50	1.4 to 5.4 mph	1/6-g Weighted	75 lb	Shirtsleeve
10:21:18	1.4 to 5.4 mph	1/6-g Weighted		Shirtsleeve
11:00:31	1.4 to 5.4 mph	1/6-g Weighted	25 lb	Shirtsleeve
11:31:32	1.4 to 4.4 mph	0.32-g Weighted		Shirtsleeve
12:07:10	1.4 to 5.4 mph	1/6-g Weighted	50 lb	Shirtsleeve

23-May				
	Varied Pressure			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
14:07:30	2.2 to 6.2 mph	3.0 psi	1/6-g	Suited
14:32:38	2.2 to 6.2 mph	5.0 psi	1/6-g	Suited
14:58:42	2.2 to 6.2 mph	1.0 psi	1/6-g	Suited
15:30:46	2.2 to 6.2 mph	6.5 psi	1/6-g	Suited

25-May				
	Varied Weight			
Start Time	Speed	Suit Pressure	Gravity Level	Conditions/Notes
13:19:39	2.2 to 5.2 mph	4.3 psi	0.32-g	Suited
13:51:27	2.2 to 5.2 mph	4.3 psi	0.22-g	Suited
14:24:21	2.2 to 6.2 mph	4.3 psi	0.12-g	Suited
15:01:24	2.2 to 6.2 mph	4.3 psi	1/6-g	Suited
15:25:02	2.2 to 5.2 mph	4.3 psi	0.27-g	Suited
15:48:13	2.2 to 6.2 mph	4.3 psi	1/6-g	Suited – waist locked

24-Jul				
	Varied Mass			
Time	Speed (mph)	Gravity	Added Mass	Conditions/Notes
13:12:30	2.2 to 6.2 mph	1/6-g Weighted		Shirtsleeve
13:48:48	2.2 to 5.2 mph	0.27-g Weighted		Shirtsleeve
14:19:51	2.2 to 5.2 mph	0.32-g Weighted		Shirtsleeve
14:59:51	2.2 to 6.2 mph	1/6-g Weighted	75 lb	Shirtsleeve
15:34:01	2.2 to 6.2 mph	1/6-g Weighted	50 lb	Shirtsleeve
16:09:43	2.2 to 6.2 mph	1/6-g Weighted	25 lb	Shirtsleeve

Hardware Anomalies and Test-related Delays

1. On April 9, 2007, the treadmill vendor was called in to make some minor adjustments to the internal force platform mounting structure inside the treadmill deck, as one of the force plates had come loose and, therefore, was producing corrupt GRF data. The adjustment improved the quality of data received from each of the four AMTI force platforms for the remainder of the test.

2. One scheduled run had to be canceled the day of the test before starting because of data collection problems with the Vicon motion capture system, which is maintained and operated by the ABF. The system manufacturer (located on the West Coast) had to be contacted, shortly after which the problem was resolved and the system was back in operation in time for the test the next day. No other problems or test delays were experienced with this system for the remainder of the test.

3. One test subject was replaced with another crew member test subject early in the test (after his first suited run) because of a suboptimal MKIII suit fit and general comfort. Until more suit sizing elements are procured (specifically boots, HUT, and hard lower torso (HLT) assemblies), current suit size will continue to a major driver in subject selection for tests involving the MKIII suit.

4. The suited run on April 11 had to be discontinued before conclusion of the planned test activities because of a structural problem discovered on the MKIII suit. A crack was found on one of the four bosses (the attachment points for the PLSS mockup and the Spider Gimbal System) located on the lower left corner of the composite hatch. On finding this, the test team immediately stopped the test and the subject egressed the suit. The hatch was removed from the suit and taken to the Nondestructive Evaluations Laboratory in the Materials and Processes Branch (ES4) on site at JSC for further inspection. X-ray analysis found evidence of cracking and dense foreign matter/inclusions in the composite material in all four bosses. For more information regarding this analysis, contact Kenneth Hodges (ES4). After the in-house analysis had been performed, the hatch was sent back to the manufacturer (AIR-LOCK, Inc., Milford, CT) for repair. Meanwhile, the older, heavier cast aluminum hatch was placed on the suit for the remainder of the test activity.

5. The waist bearing and upper-thigh bearings on the suit began to show evidence of accelerated wear-and-tear because of the number of cycles placed on them during this test series. Energy dispersive spectroscopy (EDS) analysis performed by ES4 of the blackish-colored debris found inside the waist bearing after only about 20 hours of testing (half the time required for a full maintenance cycle on the suit hardware per CTSD-ADV-197 and/or JSC-33497 [not publicly available]) showed the black debris was mostly oxidized aluminum mixed with some Braycote® (a common lubricating material), the presence of which meant that the waist bearing was wearing down at an accelerated rate as used in this test. As a result, the suit technicians had to perform a more detailed maintenance procedure than is usually required between tests (within the normal 40-hour maintenance cycle). This finding also resulted in a change to the test plan, which originally called for testing at 0.0 psid, as that specific test point proved to be too hard

on the suit bearings. The test point was changed to be conducted “vent pressure,” or 1.0 psid, to protect the functionality of the suit and the bearings.

6. Some minor test delays were caused when reflective markers, used as part of the motion capture data collection system, did not stay on the suit very well at lower pressures, thus causing the team to have to pause the test activity several times to replace the critical markers at the lower pressures.

7. During the set up of the entire test area, the test team learned (by trial and error) that the power supply provided by the SVMF is not “clean” and, therefore, requires power conditioners to provide reduced noise in the power supplied to the test and data collection equipment, which results in cleaner and more accurate test data.

8. Because of the large number of planned test days (21 total), and the number of MKIII suit fit checks (four total, scattered throughout the test) required for this test activity, test scheduling was susceptible to and compounded by facility availability, crew availability, suit maintenance requirements, and suit availability (as it was being used in other tests and fit-check activities were taking place in the same time frame). In general, aligning all three of these factors and accomplishing 21 days of testing within the original test schedule proved a challenging task. As a result, the test schedule was often changed and/or delayed.

Overall Test Summary

All of the test objectives planned for this test were completed without incident. Excellent participation and cooperation were exhibited by all parties involved through all aspects of test planning and execution. Recommendations and conclusions from this test will be documented in the final technical report following video review and debriefs with the SE&I teams from the EVA Systems Project and EPSP.

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13. ABSTRACT *(Maximum 200 words)*

Our understanding of suited human performance in reduced-gravity environments includes observations from Apollo lunar surface extravehicular activities (EVAs) and studies in partial-gravity simulation environments. In developing design requirements for the next-generation lunar EVA suit, we initiated a series of tests to understand human performance and suit kinematics under simulated lunar EVA conditions. Study results will provide evidence-based recommendations for suit weight, mass, center of gravity (CG), pressure, and suit kinematic constraints. The EVA Walkback Test (EWT) used the Partial Gravity Simulator (POGO) in the Space Vehicle Mock-up Facility and the Mark III (MKIII) spacesuit. The MKIII provided dynamic ranges of motion for many planetary tasks. Results from EWT showed initial estimates for total metabolic cost of suited locomotion in the reduced-gravity lunar (1/6-g) and martian (3/8-g) environments and preliminary biomechanical parameters. For Integrated Suit Test-1 (IST-1), suited conditions had a constant CG location and suit mass while suit offload, pressure, and suit kinematic constraints varied. For unsuited conditions, the subject's mass was held constant while offload was varied or the subject's weight was held constant while the subject's mass was varied. This final report presents key findings of IST-1 as related to suited/unsuited human performance of treadmill locomotion on POGO.

14. SUBJECT TERMS

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